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(A Manual for Seismological Engineers)

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CORRELATION METHOD OF REFRACTED WAVES
(A Manual for Seismological Engineers)

[Following is a translation of the entire manual written by G. A. Gamburtsev, Yu. V. Riznichenko, I. S. Berzon, A. M. Yepinat'yeva, I. P. Pasechnik, I. P. Kosminskaya and Ye. V. Karus, and published by the Publishing House of the Academy of Sciences USSR, Moscow, 1952]

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Introduction

During the first stage of the development of seismographic geophysical exploration, the only method that had any practical significance was the most elementary modification of the method of refracted waves - the method of first entries. This was basically due to the low level of the methods and techniques of seismological observations: on the seismograms obtained at the time, for the most part nothing could be utilized except the travel time of the first wave. Of certain significance was also the fact that information about the singularities of the propagation of elastic waves in heterogenous media was extremely scant.

The development of the method of reflected waves signified the transition to a new, more efficient observational technique for seismographic geophysical exploration. Insofar as reflected waves never produce first entries on seismograms, it was necessary to introduce into the technique of registering seismic observations improvements that would assure the interpretation of seismograms in the area of subsequent entries. This was accomplished by introducing into seismographic geophusical exploration the "correlation" method of isolating and tracing waves, as well as special measures for eliminating the interfering waves, mostly surface and sound air waves.

A correspondingly radical modification of equipment and methods of seismic observations was performed: single seismographs were replaced by multichannel seismic stations; from seismographs, amplifiers and galvanometers there was required not only high sensitivity but also a quite definite frequency selectivity and strict identity of frequency and phase characteristics; for greater reliability of wave correlation, the spacing between seismographs was decreased; the conditions of the excitation of oscillations (explosions in wells) were improved.

These improvements in the method and technique of registering seismic waves immediately produced results; the method of reflected waves quickly acquired the place of honor among other geophysical methods of exploration and almost completely replaced the method of first entries. The latter began to be utilized mostly for determining the thickness of the "zone of weathering" in connection with the need to enter corrections for this zone into the observations of reflected waves.

The superiority of the method of reflected waves over the method of first entries was completely obvious. However, there was no reason to connect this with the type of the registered waves, i.e., to consider that refracted

waves are less useful for exploratory aims than are reflected ones. This can easily be attributed to the fact that the method of refracted waves continued to be regarded as the method of first entries: consequently, those improvements which assured the success of the method of reflections were not introduced into it. It was possible to think that the effectiveness of the method of refracted waves would increase essentially if this method were based on the registration not only of the first but also of the subsequent entries.

The creation of the method of reflected waves prepared the initial technical foundation for the development of the method of refracted waves within this context. If it did not make sense to adopt techniques of reflection registration for registration of the first entries, such adoptions were very expedient for the registration of subsequent phases of refracted waves. First of all, it was necessary to utilize the correlation principle of isolating and tracing waves in the area of subsequent entries, and the method and techniques of seismic observations that correspond to this principle. Thus, the thought of providing the method of refracted waves with the same technical means as the method of reflected waves arose naturally.

The considerations cited here have forced the author of these lines, together with a group of co-workers of the Division of Physical Methods of Exploration of the Institute of Theoretical Geophysics (currently the Geophysical Institute), Academy of Sciences USSR, to undertake the create of a new modification of the method of refracted waves, based on the registration of first and subsequent entries of refracted waves. This modification was called the correlation method of refracted waves (abbreviated CMRWO in order to stress the significance of the correlation principle of isolating and tracing waves in the new method.

The experiments of the first few years (1938-1940) gave hopeful results. The possibility and practicality were determined of introducing the correlation principle into the method of refracted waves, and method and practical procedures of refracted-wave registration that correspond to it.

It was established that a transition from the method of first entries to CMRW leads not only to an increase in the accuracy of exploration results but also to an essential expansion of the area of solvable problems. For example, by means of CMRW, under certain conditions, "shielded" layers may be studied, which are inaccessible in principle to the method of first entries.

During the first years, the CMRW was developing under the great influence of the method of reflected waves, while mastering the techniques of the latter. Later, in some

problems of theory and practice, CMRW outran the method of reflection. As an example, the problems of utilizing the dynamic peculiarities of seismic waves and methods of phase correlation may be cited, which are developed in much greater detail and much more fully in the CMRW than in the method of reflections. The dynamic correlations on seismograms are utilized in CMRW in the area of utilizing the dynamic peculiarities of recordings, as well as some others in their turn, will also turn out to be useful for the method of reflected waves.

The exploration possibilities of the CMRW and the method of reflections were compared. It was found that both methods have their particular relative advantages and drawbacks, but on the whole both methods are approximately equally valuable. They should be regarded not as rivals but as mutually complementary methods, whose combined utilization may give especially fruitful results.

One of the main virtues of CMRW lies in the fact that it enables one to determine reliably one of the physical parameters of refracting layers, namely: the speed of propagation of seismic waves along them. The knowledge of this parameter considerably eases the construction of seismic sections and their geological interpretation.

During a number of years of methodological and experimental production work on CMRW in various regions of the USSR, both equipment and the method of field observations and interpretation of the results were developed; and many problems of the physics of elastic waves, important for the development of the method were studied. The usefulness of CMRW was established for the solution of a great number of important practical geological exploration problems in the exploration and search for petroleum, coal and ore deposits. Some other areas of CMRW utilization were projected; in particular, there is reason to believe that CMRW will also turn out to be useful for the solution of geological engineering problems, particularly in searches connected with the great developments of communism.

CMRW has already begun to be utilized in industry. Later, wider development of work on the CMRW should be expected. In connection with this, the need of writing a manual of CMRW arose. Until now, there were only periodical articles on separate problems; furthermore, the brevity of the statements and disconnectedness of articles made it difficult to become acquainted with the method as a whole. This book is the first attempt at unification of the materials on CMRW in the possession of the Geophysical Institute, and, on this basis, at giving a systematic account of the method to serve as a manual in conducting field work and in interpreting its materials.

This manual of CMRW is basically intended for seismological engineers who are acquainted with the method of reflected waves. This allowed abbreviating the text of the manual considerably and, at the same time, comparing the peculiarities of both methods more fully.

Though the authors of the manual took part jointly in the development of the whole method, the work of composing the text of the manual was divided among the authors by chapters: G. A. Gamburtsev wrote the Introduction and Chapter I; Yu. V. Riznichenko, Chapters V, VII and Section 4 of Chapter VI; I. S. Berzon, Chapter IV and Chapter VI (except Section 4); A. M. Yepinat'yeva, Chapters VIII and IX; I. P. Kosminskaya Chapter III and Sections 1-5, and 6 of Chapter III (in collaboration with I. P. Pasechnik); I. P. Pasechnik, Chapter II and Section 7 of Chapter III; and Ye. V. Karus, Sections 8 and 9 of Chapter III.

CHAPTER I

Physical Principles of CMRW

The correlation method of refracted waves (CMRW) is a seismic method of studying the geological formation of a medium in the interval of depths from several meters to several kilometers. By means of the CMRW, the depths and shapes of seismically refractive boundaries are determined, as well as the speed of propagation of elastic waves along them (boundary velocity). CMRW is based on the registration of the same type of waves as is the old modification of the method of refraction waves (the method of first entries; however, the method and technique of exploration of the CMRW is closer to the method of reflections.

The basic peculiarities of the CMRW consist in the following

1) in differentiation from the method of first entries, CMRW utilizes not only the times of first entries on seismograms, but also the times of arrival of subsequent groups of refracted waves;

2) in the CMRW, as in the method of reflected waves, the principles of phase correlation of waves are utilized in tracing the waves on seismograms;

3) in the CMRW, as in the method of reflected waves, the selection of the system of seismic observations is subjected, as a rule, to the requirement of obtaining correlated complete systems of hodographs;

4) in CMRW, the dynamic characteristics of the waves (intensity, form) are utilized more widely than in the method of reflected waves; furthermore, not only for carrying out phase correlation but also with the aim of directly relating dynamic features on seismograms with the peculiarities of the structure of the medium under study;

5) the method and technique of exploration according to CMRW provide for the possibility of combined utilization of CMRW and the method of reflected waves.

The basic features of CMRW indicated here are determined by the physical peculiarities of refracted waves in actual geological media. These peculiarities were made clear mostly as a result of analysis of wide experimental field materials, accumulated by the Geophysical Institute of the Academy of Sciences USSR over a number of years of work on CMRW under various geological conditions. Further on, we shall pause at some of these peculiarities, those which have a decisive significance for the development of the method and technique of exploration of the CMRW.

1. The Types of Refracted Waves

Frontal Waves and the Mechanism of Their Formation. In the CMRW (and generally in seismic exploration) refracted waves, in the sense in which they are usually understood in physics courses, are found very rarely. Indeed, if the points of excitation and reception of elastic oscillations are located on one side of a seismic boundary which takes place most of the time in seismic exploration, tue usual refracted waves may be discovered only in the case of a concave refracting boundary. Only in fault seismography, where the points of excitation and reception of oscillations may be located on different sides of the studied boundary will suitable conditions for registration of these waves exist.

These waves, which in seismology are usually called refracted waves, strictly speaking belong to one of the types of diffracted waves, namely: to the so-called frontal waves (or to Mintrop waves, in the old terminology).

From now on, we will still keep for them the name refracted waves, and only in individual cases, when it will be necessary to stress their difference from the usual refracted waves or other types of diffracted waves, will we call them frontal waves.

The physical interpretation of a frontal wave may be given in an elementary form. As close analogues of the frontal wave in seismism, there may serve both the head or ballistic sound wave that originates in the flight of a missile with a speed exceeding that of sound, and the light radiation, discovered by S. I. Vavilov and P. A. Cherenkov /12/, observed in the motion of an electron in a medium with a speed higher than the speed of light.

A still closer analogy may be found in the following mental experiment /19/. Let us assume that in a hard, homogenous,

elastic medium a certain source of perturbation is moving with a speed that exceeds the speed of the longitudinal waves in the medium. Then "ballistic" longitudinal and transverse waves will originate in it, which, according to the mechanism of their formation, will be close to the frontal waves in seismism in the case of thin refracting layers.

Indeed, if in a homogeneous, elastic medium there is a thin layer in which the speed of propagation of elastic waves is greater than in the surrounding medium, then the perturbation propagated along the given layer will obviously induce in the surrounding medium the appearance of the same "ballistic" or frontal waves. The existence of radiation from the layer into the medium follows from the boundary conditions, as a consequence of which the components of elastic displacements and stresses on both sides of the division boundary at the very boundary line must be correspondingly equal (continuity of displacements and stresses).

In Fig. 1, the fronts of the developing waves are pictured for that simplest of cases when the focus of perturbation V is located in the layer itself. The receiver which is located at some point P outside of the layer, will note the head wave. Noe let receiving point P change places with excitation point B of oscillations, preserving the corresponding characteristics of directivity. Then, as a consequence of the principle of reciprocity /13/, we will discover that, with excitation of oscillations at point P, there will exist at point B the same perturbation as in the first case. This explains the transmission of elastic energy not only from the layer to the surrounding medium but also from the medium to the layer.

Combining both of these cases, we could obtain the full kinematic picture of frontal wave propagation. However, with this aim, let us examine a still simpler case, namely: the case of one boundary that divides two half-spaces. Let us assume that the focus of oscillations is in the medium with a smaller velocity of propagation of seismic waves. In Fig. 2, the fronts of the longitudinal frontal waves obtained in this case are shown, as well as those of the straight and reflected longitudinal waves. As follows from elementary computations based on the application of the laws of geometric seismics, a detachment (leading) of the fronts of waves in the second medium by the fronts of the waves in the second medium by the fronts of the waves (straight and reflected) in the first medium takes place outside of sector AA'. Precisely, this detachment leads to the appearance of additional radiation in the first medium (i.e., frontal waves), since otherwise the conditions of continuity of stresses and displacements would be disrupted. Inside the area AA', the fronts of straight and reflected waves in the first medium will merge with the fronts of refracted

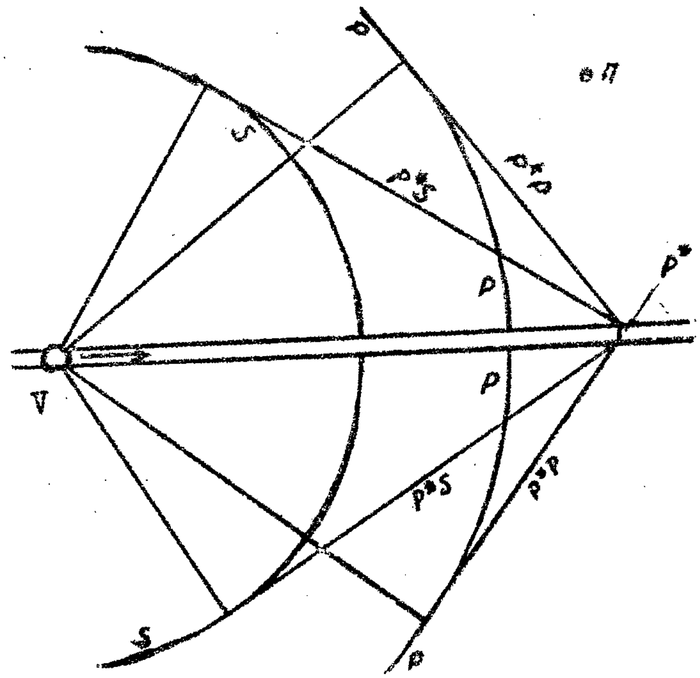


Fig. 1. Frontal waves in the case of a thin layer. P* and P are correspondingly longitudinal waves in the layer and in the containing medium; S is the transverse wave in the medium; P*P is the longitudinal frontal wave produced in the medium by the longitudinal wave in the layer; P*S is the transverse head wave in the medium, produced by the longitudinal wave in the layer.

For simplification of the drawing, it was assumed that the focus V does notstimulate transverse waves in the layer.

waves in the second medium. Thus, in this area necessary conditions for formation of head waves will not exist. It follows that head waves will be observed only at distances of focus of perturbation which exceed

$$x_o = 2h \text{ tg } i_{12} \tag{1}$$

where h is the distance between the line of observation and the limit of division

$$i_{12} = \text{arc sin } \frac{a_1}{a_2} \tag{2}$$

a_1 and a_2 are the velocities of longitudinal seismic waves in the upper (a_1) and the lower (a_2) half-spaces.

Let us call the angle i_{12} the critical angle instead of the term "the angle of complete internal reflection", which clearly does not correspond to the physical essence of the phenomenon.

For formation of head waves, aside from the condition $a_2 > a_1$, it is essential that the source of oscillations is a point source which induces the spherical waves.

Upon incidence of plane waves on the boundary of division, the detachment of the fronts would not take place and, corresponding to this, the frontal wave could not occur.

Interchange Refracted Waves. In case of one boundary line, aside from purely longitudinal P_{121} and purely transverse S_{121} refracted (frontal) waves, six types of interchange (longitudinal-transverse) refracted waves may exist: $P_{12}S_1$, $P_1S_2P_1$, S_1P_{21}, $S_{12}P_1$, $S_1P_2S_1$ and P_1S_{21} /14/. Kinematic

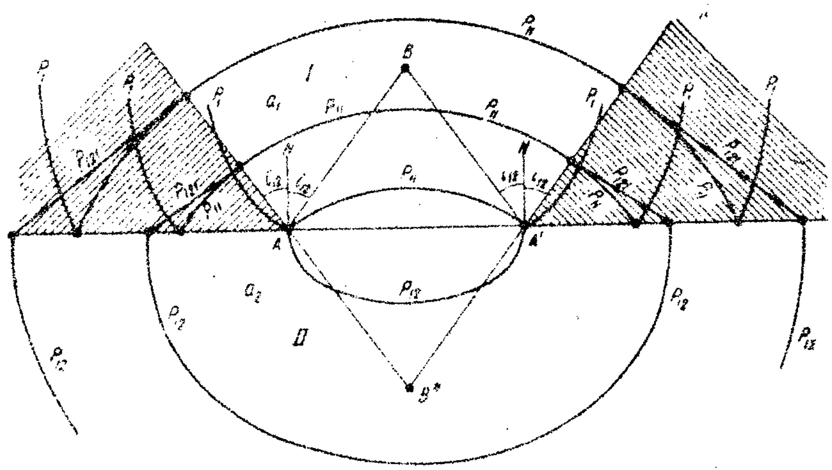


Fig. 2. The formation of frontal waves in case of flat boundary of division. P_1 - direct wave (in medium I); P_{11} - reflected wave (in medium I); P_{12} - refracted wave (in medium II); P_{121} - frontal wave (in medium I); the region of existence of frontal waves is crosshatched: a_1 and a_2 - the velocities of waves in medium I and II; B - source of waves; B* - mirror image of the source; N - normal to the border line of division; the critical angle is $i_{12} = \arcsin \frac{a_1}{a_2}$

(i.e., those based on the laws of geometric seismics) conditions of existence of all eight types of waves are cited in Table 1.

Table 1

Type of Wave	Condition of Existence
P_{121}, $P_{12}S_1$, S_1P_{21}	$a_2 > a_1$
P_1, S_{21}, $S_{12}P_1$, $P_1S_2P_1$	$b_2 > a_1$
$S_1P_2S_1$	$a_2 > b_1$
S_{121}	$b_2 > b_1$

a, b - the velocities of longitudinal and transverse waves, respectively.

The limits of the areas of existence in each concrete case may be easily determined from the values of critical angles and from the position of the oscillation source in respect to the boundary of division.

Among the enumerated waves, as it will be told in detail further on, the purely longitudinal refracted waves P_{121} have the basic significance in investigations with the OMRW.

Refracted waves in case of non-planar boundaries of division. Above, we discussed waves connected with the plane boundary of division. The picture changes in principle in case of the boundary if division assumes concave or convex form. In the first case, the frontal wave will be replaced with a wave which experiences diffraction not only at the boundary of division, but also underneath it (Fig. 3). In the second case, the frontal wave will be replaced with the simple passing refracted (more accurately, twice refracted) wave.

In the change of the curvature of the boundary of division, there will exist an uninterrupted transition from waves of one type to waves of another type.

There are no experimental data up till now which would allow to speak of some essential differences in the form of oscillations and intensity of waves of these three types.*

In other types of the irregularity of the boundary of division diffracted waves of still more sharply defined types may exist. Especially important for seismic investigations is the case of a step, when diffraction from the corner is observed. The waves which aris in this case, according to their intensity and form of hodograph differ sharply from the waves of other types.

The types of refracted waves in layered medium. In the simplest case of geological structure it is always

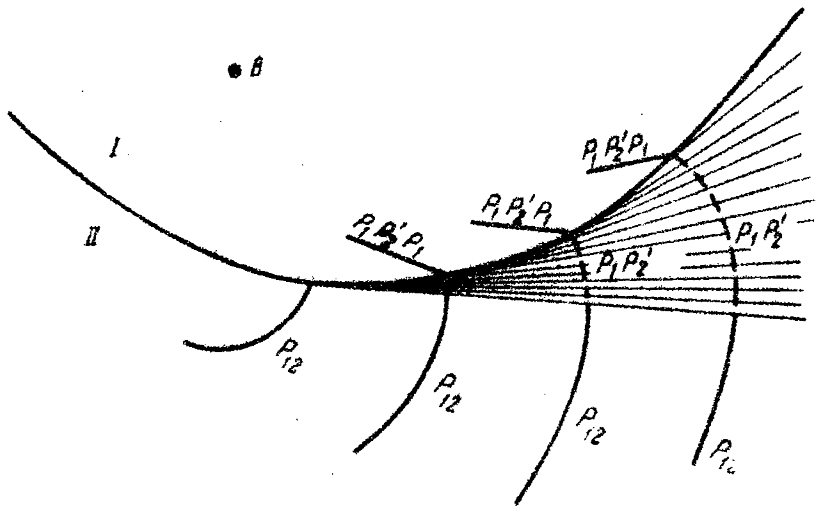


Fig. 3. The manifestations of diffraction in the case of concave separation boundary. P_{12} - refracted wave in medium II; P_1P_2' - diffracted wave in medium II; $P_1P_2'P_1$ - frontal wave in medium I complicated by the manifestations of diffraction in medium II.

necessary to bear in mind the existence, aside from the boundary of division which is under study, also the free surface - surface of the Earth. In this case, the types of frontal waves will remain the same as before, but to them waves will be added that could be called refracted-reflected. Field materials of seismic investigations, as well as experiments of modelling of seismic waves,point to the possibility of existence first of all of purely longitudinal refracted-reflected wave; furthermore, the reflection may take place in the zone of the source, as well as in the zone of the receiver of oscillations (Fig. 4). In the case of horizontal boundary of division, both these waves coincide with respect to time, and condition the appearance of one wave of double the amplitude.

On the basis of kinematic considerations, it could be possible to assume that the number of types of waves increases

*(on previous page) The investigation of this problem is made difficult because, in practice, one deals, for the most part, with refracted waves connected with the thin layers. Since, in this, the waves "glide" along the boundaries of division, it is immaterial whether the boundaries of division will be concave or convex; in both cases, the type of waves will remain the same.

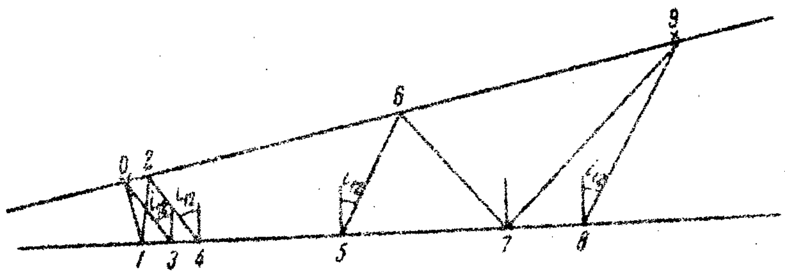


Fig. 4. The path of reflected-refracted waves. 0389 - path of simple refracted (head) wave; 012489 - path of reflected-refracted wave; 035679 - path of refracted-reflected wave.

greatly, if there will be not one but several boundaries of division under the free surface. For example, in the case of two parallel flat boundaries of divisin, the maximum number of kinematically possible refracted waves is determined by eight types of waves, connected with the first boundary of division, and 32 types of waves connected with the second boundary of division. The addition of the third boundary of division may increase the number of types of refracted waves still by 128.

In actuality, such an abundance of wave types is not observed. Of the whole multiplicity of possible refracted waves, the purely longitudinal refracted waves, i.e., waves of types P_{121}, P_{12321}, etc., basically remain. This is connected with the following causes:

1) the foregoing maximum number of types of refracted waves will be kinematically possible only in that case if the velocity of transverse waves in each subsequent layer is larger than the velocity of longitudinal waves in the preceeding (above) layer. Assuming approximately the ratio of velocities of longitudinal and transverse waves to be equalto two, it is possible to say that the kinematic conditions of the existence of all types of refracted waves will be satisfied if the velocity of longitudinal waves in each subsequent layer will be larger than the velocity in the preseeding layer by twice or more. In practice, such sharp velocity differentiation is found very rarely, which greatly reduces the number of wave types usually observed on seismograms;

2) upon excitation of oscillations by means of explosion, mainly longitudinal waves originate which allows to exclude from examination those types of waves whose symbols start with the letter S;

3) in actual geological conditions, in view of comiderable gradient of velocity, the seismic rays at the surface of the earth have an almost vertical direction. Due to this, the vertical seismographs react for the most part to longitudinal waves, what allows to exclude from examination those wave types in whose symbols end with the letter S;

4) the conditions of refraction at the intermediary boundaries of division are not favorable for formation of interchange --- longitudino-transverse refracted waves. As follows from the examination of examples, computed according to the known formulas of reflection and refraction of plane waves, the intensity of interchange refracted wave is small in comparison to the intensity of homogenous (purely longitudinal or purely transverse) refracted wave, especially in those cases when the velocity of seismic waves on both sides of the boundary of division are not sharply differentiated from each other. Thus, the energy conditions of refraction at the intermediary boundaries of division also decrease sharply the number of waves which may be observed in practice.

Aside from the four groups of causes cited here, it is possible that some other causes, for example greater absorption of transverse waves as compared with the longitudinal ones, may have an equally serious significance. Together with this, it is not possible to guarantee a total absence on seismograms of some types of interchange refracted waves.

The interchangeable refracted waves in majority of the cases are, probably, obscured by the purely longitudinal refracted waves; however, under conditions favorable for them, (for example, when the interchange wave is divided from the basic longitudinal refracted wave by a sufficient interval of time, and when, on the interchange wave, other longitudinal refracted waves are not superimposed), the interchange refracted waves, generally speaking, may form sufficiently clear phases. This circumstance requires special care in interpretation of weak phases after the arrival of the intense ones.

The basic conclusion is in that the transverse and interchange refracted waves, under usual conditions of excitation and registration of seismic waves, must possess considerably smaller intensity than the purely longitudinal refracted waves. This is confirmed by the experimental materials; in practice, transverse and interchange waves are found extremely rarely.

Refracted Waves Which Correspond to "Shielded" Boundaries. Above types of waves were examined, the existence of which follows from the laws of geometric seismics (i.e., from kinematic conditions). It was pointed out simultaneously

that not all kinematically possible waves have a sufficient intensity.

Another que tion may be put forward: if one considers the wave nature of the phenomenon, the comparability of the lengths of seismic waves with the dimensions of geologic formations (for example, with the thickness of layers) is it not reasonable to expect then the appearance of some new waves, "unforeseen" by the geometric seismics or "forbidden" by it.

Already, the first works on the CMRW has led in this respect to interesting practical conclusions /16/. Previously, proceeding from the laws of geometric seismics, the existence of refracted waves, connected with some definite boundary, was considered impossible, if at least one of the layers located above the boundary (independently of its thickness) posesses greater velocity of seismic waves.

Such boundaries of division, according to the laws of geometric seismics, must be shielded.

Experiments with the CMRW showed that the refracted waves of the given type, if the thickness of shielding layer does not exceed half of the length of wave, not only exist but are frequently characterized by greater intensity and may be utilized for prospecting aims.

Analysis and generalization of materials collected in prospecting on CMRW on shielding action of layers of different capacity, depending on the velocity characteristics of medium and length of seismic waves, was conducted in reference /10/.

2. The Intensity of Refracted Waves.

<u>The Correlation of Intensity of Refracted and Reflected Waves</u>. The reflecting boundary is not always a refracting one. For example, on the surface of a layer which posesses a smaller velocity of seismic waves than the medium which covers it, head waves will not form but only the reflection of seismic waves will take place.

Inversely, the refracting border also is not always reflecting. For example, "rough" surface of the division will not give correct reflections but will only disseminate the seismic waves; together with this, the same surface may condition the appearance of regular refracted (frontal) waves.

Thus, the ratio of intensities of refracted and reflected waves may be equal to zero as well as to infinity.

Let us pause on an especially interesting case when the seismic boundary is simultaneously refracting and reflecting.

As it is known, hodograph of refracted waves at its initial point touches the hodograph of reflected waves which

belong to the same boundary of division. Thus, before the initial point, i.e., closer to the point of explosion, proceeding from the laws of geometric seismics, only reflected waves should exist. Experimental field data confirms this.

After the initial point, i.e., further from the point of explosion, proceeding from the same laws, the waves of both types should exist.

However, as the experiment of the CMRW utilization in various regions of USSR and under various conditions demonstrates, the reflected waves behind the initial point, as a rule, are not observed, and only refracted waves are registered. Exceptions from this general rule were noted in field observations only in very rare cases /53/.

Just the same, the possibility of observing the reflected waves after the initial point is not excluded in principle. Except for rare and for the most part unclear cases of field observations of reflected waves in this area, this is confirmed by laboratory experiments /6/ on models of stratified media with sharply differentiated densities and velocities in separate layers, when the reflections in this area are clearer.

In the last works of G. I. Petrashen' /46/ and N. V. Zvolinskiy /39/, devoted to the dynamic theory of frontal waves, it is shown that after the initial point one might really expect the prevalence in intensity of refracted waves over the reflected waves.

In some cases, the phases of reflected waves as if without interruption pass over into the phases of refracted waves without any essential changes in form and intensity of oscillations.

In other cases, in the transition zone a noticeable increase of amplitudes is observed which pointsout that the initial point of hodograph of refracted waves has a dynamic significance.

<u>Subsiding of intensity of refracted waves with distance.</u> Proceeding from the theoretic works of L. M. Brekhovskikh and L. I. Petrashen', in the case of one flat boundary of division in ideally elastic medium, the amplitudes of head waves should subside in inverse proportion to the square of distance (in first approach).

For more complex cases of medium formation, theoretic computations are lacking. Experimental data point out that in many cases the decrease of the amplitude with the distance in real geologic media may be expressed by the formula

$$A(x) = A_0 \frac{e^{-Kx}}{x^n},$$

where n varies within the limits of from 1 to 2 /8/. The appearance of exponential coefficient e^{-kx} may be connected with the absorption of elastic waves. In this case, the coefficient k is proportional to the frequency of elastic waves.

The fact that the degree of attenuation of refracted waves with distance, as practice shows, does not impose limit tions on the depth of prospecting is especially important for the development of the CMRW*

With this, it is necessary to note that the need in prospecting with the CMRW to conduct seismic observations at distances from the point of explosion greater than in prospecting according to the method of reflected waves (in equal depth of prospecting) forces to:

a) use the equipment which possesses greater sensitivity than the equipment of the method of reflected waves;

b) to keep strictly the conditions of quiet on the profile avoiding the proximity of disturbance sources, such as: working drill holes, highways, inhabited places, etc.;

c) to select the most effective conditions of oscillation excitation (explosions in drill holes, in reservoirs).

<u>The Case of a Thin Layer</u>. For a thin layer (in respect to the length of the wave), the law of subsiding of intensity of head waves with the distance may be formally expressed by means of the same formula (3). However, the physical significance of the coefficient k may be a different one. In the given case, the appearance of the exponential term may be connected not only with the absorption of elastic waves, but also with radiation from the layer into the medium. Then

$$k = k_1 + k_2,$$

where k_1 is a term which depends only on absorption and is proportional to the frequency of elastic waves, and k_2 is a term which depends only on radiation.

*The experiments in depth seismic probing of the earth's crust, performed by the Geophysical Institute AS SSR in 1949 and 1950, established the possibility of study of refracting boundaries which are located at the depth of several tens of kilometers.

For one boundary of division, which is equivalent to the layer of very great thickness, $k_2 = 0$. On the basis of experimental data, it is possible to consider that for the thin layer of the given thickness k_2 will be the greater, the smaller is the frequency of elastic waves /8/.

In correspondence with this, the function $k(\omega)$ may have minimum, i.e., there may be a certain optimum frequency in which the head waves may experience the smallest decrease with the distance. This optimum frequency will be different for layers of different thickness and different matter composition (See 3).

The intensity of refracted wave connected with a thin layer is the smaller the smaller is the ratio d/λ - the thickness of the layer to the length of the wave. However, very thin layers may still be noticed. In $d/\lambda = 0.1$ (in some cases even smaller) the refracted waves which correspond to these thin layers may be isolated on seismograms /10/. Due to this, clear refracting boundaries are frequently discovered there where, on the basis of the method of reflected waves data and even on the basis of seismic coring measurements, the medium appears to be almost homogeneous /27/.

<u>The Effects of Abnormally Strong Fading of Refracted</u> Waves. The following wave picture is frequently observed. At some distance from the point of explosion in the initial part of seismogram, there are two groups of waves (A and B), approximately equal in intensity and close to each other in apparent velocities. In increase of the distance from the point of explosion, such fast fading of waves A takes place that they become barely noticeable on seismograms, at the time when waves B posess, as before, sufficient intensity.

Upon further increase of the distance, waves A disappear on seismograms for all practical purposes. The impression is being created that the first entry is formed already by waves B, even if actually waves A exist as before and preceed waves B. This is often successfully proven by means of an extremely strong explosion which allows to "drive out" the weak preliminary phases which belong to waves A. If still greater distances from the point of explosion are taken, then waves A disappear completely on the seismograms despite the utilization of still stronger explosions. The disappearance of waves A, as the analysis of observation results and the comparison with teological data show, cannot be attributed to the disappearance of the refracting boundary connected with wave A, but only to the abnormally great fading of waves A.

Numerous replacements of waves which appear to be a part of the area of first entries are frequently observed; furthermore, this replacement of waves is not explained by

the fact that the waves overtake each other but by the effects of abnormally strong fading.

The manifestation of abnormally strong fading cannot be explained by the abnormally large absorption of elastic waves in separate cases, since this phenomenon is frequently observed in the layers which are characterized by small absorption.

Here, the main role is played not by the absorption of elastic waves in separate cases, since this phenomenon is frequently observed in the layers which are characterized by small absorption. Here, the main role is played not by the absorption of elastic waves, but by their radiation from the layer into the surrounding space. The described manifestation may be basically connected with the small thickness of the refracting layer as compared with the length of the wave. Besides, other factors may act also, such as: the existence in the refracting layer of the vertical gradient of velocity, the peculiarities of the form of surfaces which circumscribe the refracting layer and some others.

If phase correlation of refracted waves is not utilized, then, owing to the effects of wave fading, serious errors may arise in the plotting of the hodographs and, correspondingly, in the geological interpretation of observation results. It is necessary to conduct the phase correlation of refracted waves, the first ones, as well as the subsequent ones, even in those cases when, for construction of crossection, it appears possible to utilize only hodographs of the first entries.

Abnormally strong fading of waves and, correspondingly, the disappearance of the first entries, deprive the old modification of the method of refracted waves - the method of first entries - of physical definiteness.

In the CMRW, the manifestations of abnormally strong fading, in so far as they may be considered differentiated, do not lead to the errors in interpretation and do not even limit the possibility of the method. On the contrary, in some cases which are rather frequently met in practice, they aid in the study of the medium formation since disappearance of one wave may aid the tracing of others.

<u>The intensity of refracted wave in dependence on the correlation of velocities of seismic waves.</u> This problem has not yet been investigated theoretically. It is possible to only point out that in $V_2/V_1 \gg 1$ the intensity of refracted waves must decrease with the increase of V_2/V_1 becoming 0 in $V_2/V_1 = \infty$)V_1 and V_2 are respectively the velocities of seismic waves in upper and lower medium).

Indeed, when $V_2/V_1 = \infty$ the seismic waves will not penetrate into the lower medium being completely reflected from its surface. The experimental data point out, apparently, some optimum ration V_2/V_1 exists for which the

intensity of refracted waves is maximum.

The optimum corresponds to relatively small differences in velocities. Of important practical significance is that even in very small relative difference of velocities, the intensity of refracted waves is sufficiently large. By means of the CMRW the limits may be discovered at which the velocity of elastic waves increases by only several percent.

The dominating refracted waves. In contrast to waves which are subject to abnormally great fading, it is necessary to note the existence of refracted waves which exceed several times in intensity other waves in the same area of the seismogram and which preserve their dominating character over considerable segments of the profile. The existence of dominating refracted waves is a very favorable factor for prospecting with the CMRW. Due to their intensity the dominating waves are not subject to distortions in interference with others (non-dominating) waves. They may be reliably be followed in the area of initial, as well as in subsequent, entries. In some cases, the correlation of phases of dominating waves is possible even in the presence of breaks in the profiles.

Besides, the possibility of identification of these waves in disconnected regions of observations frequently appears.

The presence of dominating refracted waves in the case of a medium which contains thin layers with increased velocity of seismic waves may be connected with many factors, such as: smaller absorption of elastic waves in the medium, which corresponds to the dominating waves, greater thickness of this layer, and more favorable correlation of velocities as compared with other layers.

The Connection Between the Intensity of Refracted Waves and Peculiarities of the Form of Refracting Borders. In the simplest case, the question is that in disappearance of the refracting layer together with it disappears the head wave connected with it.

In exploration with CMRW, in view of great stability of the wave picture and good correlation ability of the waves at great range, it is easy to notice the disappearance of the wave, especially if it is brought out into the area of first entries. In area survey, it is possible to follow on the observation surface a line (rather, a strip) that separates the region in which the given frontal wave exists from the region where it does not exist. In this way (after introduction of certain corrections), the region of expansinn of the layer being studied may be determined /18, 20/. In other, more complex, cases (degree, change of incline of the boundaries of division etc.), it is necessary to pay

attention to finer peculiarities of recordings.

It is necessary to note that in the method of reflections it is possible, generally speaking, to formulate analogous problems. However, their solution will be connected with somewhat greater difficulties, in particular, at the expense of the fact that the study of intensity and form of oscillations will have to be conducted in the area of subsequent entries and not in that of the first, as it is possible to do with CMRW. Besides, the study of the dynamic correlations in the method of reflections is obstructed by the character of the equipment utilized in this method (the amplitude regulator, mixer, sharp frequency characteristics).

3. The Form of Refracted Waves

<u>The Frequencies of Refracted Waves</u>. The registration of reflected waves is performed mainly in the frequency interval of 40 to 60 cycles. Under the same conditions of explosion and reception of oscillations, the refracted (frontal) waves on seismograms near to the initial point are characterized by only somewhat lower frequencies than reflected waves. The decrease of frequency may be explained by the fact that the fault at the front of the frontal wave is less sharp than at the front of the reflected wave /39/.

At distances up to 8 -- 10 km from the point of explosion in shot holes filled with water, the registration of refracted waves may be conducted at frequencies of 30 -- 40 cycles. At distances exceeding 10 -- 15 km, it is necessary to decrease significantly the frequency of oscillations being registered.

This is connected with two causes. First, in work at large distances from the point of explosion, it is necessary to perform greater explosions; with this, the intensity of primarily low frequency components of oscillations increases; the intensity of high frequency components also increases, but to a degree insufficient for compensating the weakening of energy with distance. Secondly, at considerable distances greater absorption of high-frequency oscillations as compared with the low-frequency, becomes significant.

Due to the indicated reasons, at large distances from the point of explosion, the registration of refracted waves is conducted at frequencies of 20 -- 30 cycles*

*The experiments of observations with low-frequency seismic equipment, developed at GEOFIAN /Geophys. Inst. Acad. Sci./, in connection with the tasks of depth sounding of the Earth's crust, point to the expediency of decrease of frequency of oscillations being registered at frequencies as low as 10 cycles in individual cases.

On the contrary, in probings at small depths, when the distances between the points of explosion and reception of shocks are small, there is a possibility to increase the frequencies of oscillations being registered even in comparison with those frequencies which are accepted in registration of reflected waves.

More detailed study of refracted waves and experiments of their registration in various ranges of frequencies, in particular by means of wide-band equipment, permitted to determine a very large variety of the spectrum composition of refracted waves; furthermore, not only in dependence on the distance and conditions of explosion but also in dependence on the character of refracting layers.

It was established that refracted waves which belong to different layers frequently noticeably differ in the frequency of their oscillations. This has a serious significance for the method, since it makes easier the isolation and correlation of refracted waves, as well as their correlation to the geological boundaries.

The variety of the frequency spectrum of refracted waves points to the necessity, in probings with CMRW, to have the equipment which permits to vary the frequencies of oscillations being registered in considerably greater limits than in probings with the method of reflected waves.

<u>The change of form of refracted waves with distance.</u>

It was pointed out above that in increase of the distance from the point of explosion the maximum of frequency spectrum is displaced to the side of low frequencies. However, if one does not strive to obtain at each point of observation the registration of maximum intensity (in given conditions of explosion), then, by methods of frequency filtration it is possible to obtain that, at considerable sections of the profile, the predominant frequencies of oscillations on seismograms will be preserved unchanged.

Together with this, despite the general similarity of the form of oscillations at neighboring seismograms, the decrease with distance of the sharpness of the first entry and relative decrease of amplitudes of first deviations are observed as a rule. This may be basically explained by the fact that high frequency components of oscillations endure greater absorption than those of low frequency (the coefficient of absorption of elastic waves is proportional to their frequency).

The decrease of intensity of high frequencies in the frequency spectrum of the wave will lead to softening of the sharpness of its entry. Let us note that the change of the wave form is difficult to connect with the manifestations of dispersion, since for longitudinal elastic waves the dispersion is practically absent.*

The indicated changes of the form in overwhelming majority of the cases are insignificant and do not obstruct the identification on neighboring registrations of not only the waves as a whole but also of separate oscillations in the wave, i.e., do not obstruct the conducting of phase correlation. This statement is based on the following experimentally determined property of hodographs of phases of refracted waves: if the hodographs of phases refer to one wave which is not distorted by other waves, then they are practically parallel to each other, as well as parallel to the hodograph of initial entries. The parallelism is preserved independently of those changes of the form which were noted by us above.

This property of hodographs of phases is the proof of validity of phase correlation of refracted waves. Simultaneously, from here follows the justification of application of methods of geometric seismics to the interpretation of hodographs of the phases of refracted waves.

The direction of soil dislocation in first entry. In the case of a purely longitudinal refracted wave, the dislocation of soil at the front of the wave in its approach to the surface of the Earth must be directed from below to above (what corresponds to a downward motion of inert mass of seismograph). Together with this, on seismograms, especially in the case of registration of seismic waves by means of high frequency equipment (for example, the equipment used in the method of reflected waves), a so to speak inversion of the phase of the initial deviation with removal from the point of explosion is frequently observed.

Sometimes, the impression of multiple reversal of the sign of the first deviation is created. The experiments of utilization of stronger explosions, however, show that in actuality the direction of soil dislocation at the first entry is preserved as constant and corresponds to the arrival of the wave of compression. The apparent exchange of the direction of dislocation is explained by the decrease of the

*(from bottom of previous page) One can only speak of "quasi-dispersion", which is conditioned by the stratification of medium-existence of thin layers with greater velocity of seismic waves, than in the enclosing medium. In these waves, one should expect that short waves will lead the long ones (abnormal dispersion). However, the character of the observed changes of the form of the wave with distance allows to conclude that the main role in the studied manifestation is played not by the effects of dispersion (or "quasi-derpersion") but the effects of absorption.

sharpness of the initial entry and stronger fading of the first phases of oscillations as compared with the subsequent ones. This circumstance should be always kept in mind in determining the true moment of the first entry on seismograms.

<u>The Form of Oscillations in Mutual Points</u>. The study of the problem of observance of the principle of reciprocity in seismics (13) shows that, for the preservation of the form of oscillations in mutual points, the following conditions are necessary:

1) the spectrum composition of the perturbation source in mutual points must be the same (as well as the frequency characteristics of the equipment);

2) the directivity characteristics of the source in the mutual point must be the same as the previous directivity characteristics of the receiver of oscillations at this point;

3) the directivity characteristics of the receiver of oscillations at the mutual point must be the same as the previous directivity characteristics of the source.

In the case of excitation of seismic oscillations by means of an explosion, and their registration by means of the vertical seismograph, the conditions of sections 2 and 3 are known not to be fulfilled, since the directivity characteristics of the source and receiver of oscillations are different.

These conditions would be fulfilled by exchanging of the usual explosion by a directed source of oscillations. Therefore, it is possible to expect that the differences in the form of oscillations in mutual points under usual conditions of the explosion will not be greater than in exchange of the usual explosion by a directed source.

In the majority of the cases, these differences will be considerably smaller. For example, in the case of horizontal stratification it becomes altogether unessential what are the directivity characteristics of the source and receiver of oscillations, if only they remain unchanged in transition from one point to another. The basic condition of observance of the principle of reciprocity should be considered to be condition 1, i.e., the preservation of the same frequency spectrum of oscillations in change of place of explosion. Experience shows that in practice in majority of cases it is possible to reach successfully completely satisfactory similarity of seismograms in mutual points.

<u>4. Interference Phenomena</u>

Under interference of seismic waves, we shall understand

the effects obtained as a result of the adding two or several seismic waves, and leading to the distortion of the form and amplitude of the summed waves as well as of their phase velocities.

The conditions of interference in the exploring seismics are very varied and depend on many factors. Most of them may be divided into two groups.

To the first belong the factors connected with the type of hodographs of interfering waves, for example: the location of the points of the hodograph intersection, as well as the minimum intervals of time between the neighboring hodographs.

To the second group of factors belong some physical characteristics of the waves, such as the periods of the waves and the duration of the oscillation in each wave, the correlations of the intensities of the waves and the change of these correlations with the distance.

The interference of some other waves will not be observed in that case when hodographs of entries of these waves within the limits of the sector of observations do not approach each other for a distance which is smaller than the duration of the oscillations in the wave with the smaller approach time.

But, if interference takes place, then it might lead to loss of the phase correlation of one or both interfering waves or even to the impossibility of identification of the waves before and after the zone of interference.

Later on, we shall give a comparative description of the role of interfering noise in exploration by the CMRW and by the method of reflections.

<u>Noise Due to Surface Waves and Sound Air Waves</u>. In the works on the method of reflected waves, especially acute is the problem of superimposition of surface waves on the reflected waves, as well as that of sound waves. This is overcome by means of frequency filtration, by the selection methods based on the directivity of the waves (and shifts in the wave), as well as by means of the creation of special conditions of explosion.

In the CMRW, no noise due to surface and sound waves takes place, since the waves of the given types arrive considerably later than the refracted waves. In connection with this, it is not necessary to utilize special methods of overcoming the surface and sound waves. This has a great methodological significance, since it frees the registration of refracted waves from those limitations which are peculiar to the registration of reflected waves; in particular, it allows to conduct the observations in a wider range of frequencies (including low frequencies) and it gives a greater freedom in respect to the selection of the conditions of explosion.

Interference of Refracted Waves with Each Other. Hodographs of refracted waves, even in the simplest cases of medium formation, suffer intersections. The number of points of intersection, generally speaking, increases faster than the number of refracting boundaries.

In view of this, with the appearances of interference of refracted waves with each other, one comes across this very frequently in CMRW. The method of reflected waves, in this respect, is in a somewhat more favorable position. In the case of a medium which is characterized by plane-parallel stratification, the hodographs of entries of reflected waves do not intersect with each other. The interference of reflected waves in this case is connected with the fact that, due to a large number of reflecting levels, the intervals between neighboring hodographs become smaller than the duration of oscillations in each wave.

In more complex cases of medium formation (uncorrelated stratification of reflecting boundaries, discontinuous in the horizontal direction, etc.), the effects of interference of reflected waves may have a very complex character.

Returning to the conditions of interference of refracted waves, let us note the following:

1) The physical factors of interference (mostly the correlation of intensity of waves) frequently facilitate the selection of sufficiently extended intervals of profile, free of the interfering influence, of the effects of interference; in other words, physical factors frequently relax the requirements for the selection of intervals of observation, based on the consideration of geometric factors (form of hodograph). In many cases, the phase correlation may be conducted in such zones where, on the basis of the form of the hodographs, one should expect sharp effects of self superposition.

For example, different degrees of fading of two refracted waves with distance might cause the zone of intersection of hodographs of these waves to contain in practice only one wave (the one which posesses smaller fading). As an other example, the dominating waves (See 2) may serve, the tracing of which involves no danger of interfering noise.

2) The interference manifestations are easiest to note and interpret in the area of first entries. In some cases in this area it is possible to conduct the phase correlation of waves even directly in the interference zone itself. Especially well noticeable is the exchange of waves which form the first entries. These circumstances make the area of first entries especially favorable for tracking of refracted waves. The area of "apparent first entries" which is formed in fading of the first group of refracted waves (See 2), in this respect is equivalent

to the area of true first entries.

3) In separate cases, the interference picture is weakly pronounced, especially shen the interfering waves have close apparent velocities. Frequently, as if a gradual transition from one wave to another is observed, furthermore, the phases of oscillations are tracked without obvious signs of disruption of phase correlation. In unattentive formal approach to correlation, serious errors are possible in these cases. This remark, however, refers also to the method of reflected waves, where frequently it is necessary to deal with unstable and closely placed reflecting horizons. It should be noted that in the method of reflections the discovery of hidden interfering effects the discovery of an interchange of waves is more difficult than with the CMRW.

Indeed, in the CMRW there is a possibility of checking the phase correlation by means of overtaking hodographs, the possibility of "leading out" of the tracked wave into the area of initial entries, as well as possibilities connected with the change of frequency spectrum of the oscillations being registered. I the method of reflections the means of overcoming the interference manifestations in case of waves which have close pparent velocities, one is limited only to frequency selection.

CHAPTER II

Equipment For Correlation Method of Refracted Waves

1. The requirements imposed on Seismoreceiving Equipment.

As shown in the preceeding chapter, seismoreceiving equipment in the CMRW must satisfy several additional requirements as compared with the requirements set forth for the equipment in the method of reflected waves.

The basic requirements required from the seismoreceiving equipment in CMRW may be briefly summarized in the following way.

1. In order to have the possibility to improve the correlating ability of refracted waves, to improve the resolution of recording, freeing it of interfering oscillations, in particular of microseisms, and to increase the effective sensitivity of seismoreceiving channel, the seismic equipment must have variable filtration. Besides, since the frequency spectrum of refracted waves, which correspond to the various boundaries, registered on the one and the same seismogram, changes usually in considerably greater limits than the frequency spectrum of reflected waves, then filtration in the equipment for CMRW must change in considerably broader limits than the filtration in the equipment for the method of reflected waves. The number of stages of filtration must be sufficient (not less than four or five) for that, that it is possible to realize the frequency filtration of oscillations within the limits of the whole working band of frequencies. The working band of frequencies in work with CMRW is the band from 20 to 60 cycles, and in exploration of small depths the band width is increased to 80-100 cycles.

The variable filtration, the same way as in the method of reflected waves, is realized by means of introduction of filters into the amplifiers.

2. In the correlation method, as in the method of reflected waves, the isolation and tracking of refracted waves are based on phase correlation. Therefore the equipment for work with the CMRW must be identical in respect to frequency and phase characteristics in the whole working range of frequencies. This requirement must be fulfilled for separate links of the channel (seismographs, amplifiers, galvanometers) as well as for the channel as a whole. The relative temporary phase shift for channels, as well as for separate links of these channels should not exceed 0.001 sec.

3. The equipment must be also identical in respect to sensitivity. The relative deviation of sensitivity of channels and their separate links should not exceed 5 - 10 percent. The fulfillment of this requirement allows, in equal measure, to calibrate the seismoreceiving equipment according to sensitivity and to introduce graded calibrated regulation of sensitivity of the whole channel by means of its change in only one link, for example, in the amplifier. If the records are produced with the sensitivity of the

equipment calibrated, it is possible to utilize most fully in interpretation such dynamic peculiarity of recording as change of amplitudes of various waves. See in detail about the calibrated sensitivity in Sec. 3 of this chapter and in Sec. 1 of chapter IV. The equipment must also be equipped with devices which permit simultaneous and equal change of sensitivity of all seismoreceiving channels.

4. The equipment must have sufficiently wide relative band width in order that it is possible on seismograms to isolate the subsequent entries of refracted waves, which correspond to the closely placed to each other refracting layers and separated by small intervals of time.

The relative band width, which is usually expressed in percentages, is taken to be the ratio of the width of frequency band, bounded on the frequency characteristic by two ordinates taken at the level of 0.707 of the ordinate of characteristics maximum, to the resonance frequency. If in plotting the characteristic the gain is given not in a linear scale but in decibels, then the indicated end-point frequencies should be taken at the level of ordinates which pass three decibels below the maximum of the characteristic.

In practice we consider not the band width of the whole channel, but only of the amplifiers contained in the channel. The relative band width of the amplifiers used in the CMRW, as is shown by experience, should be not less than 40 - 50 percent when the prevalent frequency exceeds 30 - 40 cycles. In registration of lower-frequency oscillations, of the order of 10 - 20 cycles, the relative width of transmission band should be increased to 60 - 80 percent.

5. The sensitivity of receiving channels should be sufficiently high - three to five times greater than the sensitivity of channels in contemporary seismic stations which are designed for work in method of reflected waves, for example, such as EKhO-1 and SS-24-48 [38, 58]. The amplifier gain should be of the order of 105-110 decibels. High sensitivity of the equipment in work with the CMRW is necessary in connection with conducting of observations on long profiles - at distances from the point of explosion to seismographs of the order of 10 km and more.

6. The equipment must be of the multi-channel type to ensure reliable correlation of waves and high production of field observations.

7. The mutual interference between the channels should not exceed one percent.

8. It is expedient to make the seismic stations usable for work with theCMRW as well as for the method of reflected waves, so that in case of need, it is possible to utilize the same stations for work on combined method of reflected and refracted waves, which allows to study most fully the geological formation of the investigated region.

2. Modification of the Modem Seismic Stations EKhO-1 and

SS-24-48 to permit their necessary utilization in the CMRW.

In connection with the wide introduction of the correlation method into the practice of seismological engineering work, the need arises of adapting for this the seismic stations of the type EKhO-1 and SS-24-48, manufactured by our industry, and designed for work primarily with the method of reflected waves.

In work with CMRW it is sometimes necessary to increase considerably the distances between the point of explosion and the instruments. Therefore it is necessary to go over to the registration of lower-frequency oscillations than oscillations which are registered in the method of reflected waves and to increase considerably the sensitivity of receiving channels.

In order to adapt the mentioned stations for work with the CMRW it is necessary to change in them the filtration, widening it on the side of lower frequencies and to increase the sensitivity of seismoreceiving channels. The change of filtration is realized by introduction of additional low-frequency characteristics, and the increase of sensitivity - by the increase of the amplifier gain. Besides, in the stations it is also recommended to introduce some other alterations and measures which allow to simplify the conducting of work with the CMRW and which aid in increasing the quality of obtained field materials. The indicated alterations in the stations EKhO-1 and SS-24-48 as experience of the work of the Geophysical Institute on utilization of given stations for work with the CMRW testifies, are rather simply realized under laboratory conditions. However, the basic alterations could be made also under field conditions by the personnel of the seismic group.

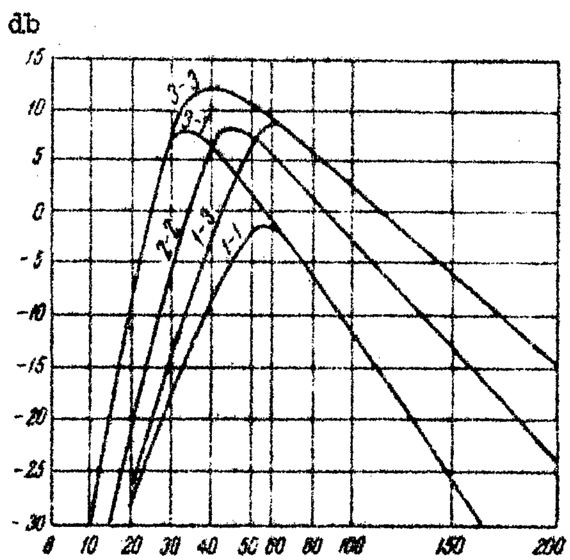


Fig. 5. Frequency characteristics of amplifier of the seismic station EKhO-1

The description of alterations in stations ECHO-1 and SS-24-48 is cited below. After these alterations the stations may be simultaneously used for work with the CMRW as well as with the method of reflected waves.

A. The alterations in the seismic station EKhO-1. The range of frequencies transmitted by the filters of amplifiers of the station EKhO-1 (see characteristics of amplifiers on Fig. 5), the band width of the seismoreceiving channels, as well as their sensitivity, are all acceptable from the point of view of utilization of the given station for work with the CMRW on relatively short profiles, of the order of 3 - 4 km and more. The dominating frequency of the waves registered with this lies usually within the limits of 30 - 50 cycles.

Thus, in work on relatively short profiles, the EKhO-1 stations may be used for work with CMRW without any alterations. For this only complete switching off of the automatic gain control (AGC) and mixer, as well as introduction of small alterations and measures, described in Sec. 3 of this chapter are necessary.

In study of depth formation, in particular in investigation of the surface of deeply embedded crystalline foundation, etc, when the observations have to be conducted on long profiles (of length of the order of 10 - 20 km), as well as in work on short profiles in the regions with especially unfavorable seismological formation of the medium (for example, in strong absorption) and in other cases, it is necessary to change over to the registration of lower frequency oscillations with prevailing frequencies of 10 - 20 cycles. In this case the necessity of decreasing the filtration of seismoreceiving channels and to increase their sensitivity arises.

The decrease of filtration is realized : 1) by means of introduction of additional low-frequency characteristics and 2) by means of displacement of low-frequency cut-off at all filtrations of the amplifier characteristics towards the lower frequencies.

The increase of sensitivity is realized by the increase of the gain of the amplifier at the expense of increase of the anode voltage and at the expense of introduction into it of additional voltage gain.

The introduction of low-frequency characteristics.

In the low frequency filter of the amplifier, whose diagram is shown on Fig. 6, the broadest band filtration 4 is shifted towards low frequencies. This allows to obtain in filtration 4 -4 new resonance characteristics with maximum of sensitivity in the region of 14 - 15 cycles and with band width from 10 - 12 to 18 - 20 cycles. This characteristics is shown on Fig. 7 dotted.

By solid lines on the same figure are shown the highest high-frequency characteristics 1 - 3 and one of the intermediate characteristics 4 - 1 of the amplifier with altered filter.

For obtaining the new characteristics, shown on Fig. 7, the following changes in the diagram of the filter of low-frequency

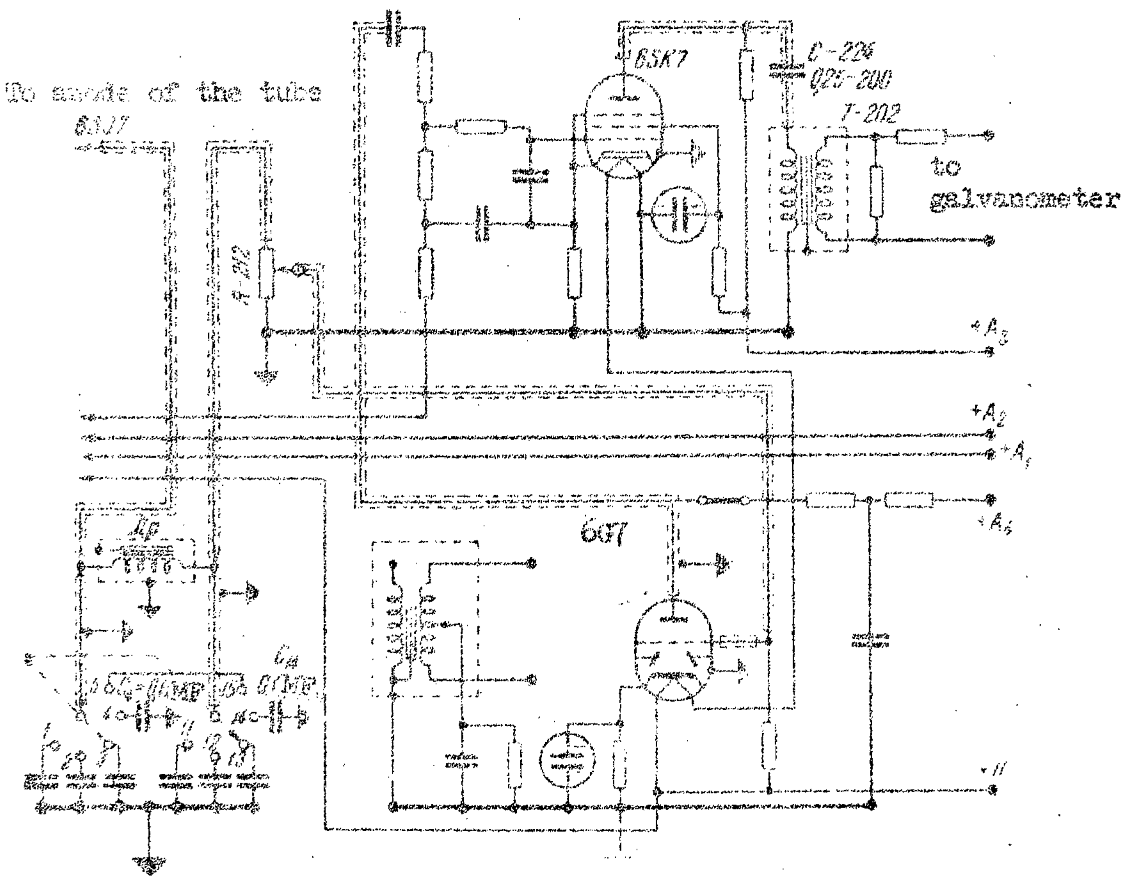


Fig. 6. Diagram of alteration: output stage, new third voltage-gain stage, of altered stage, AGC, and low frequency filter of the seismic station EKhO-1.

of amplifier are necessary. Two additional condensers with capacity of 0.1 microfarad each are added between the free terminals of the filter switch, in position 4 of the switch (on the amplifier diagram Fig. 6 these terminals are marked by numbers 4 and 14) and the amplifier chassis. On the amplifier diagram Fig. 6 these condensers are marked by C_4 and C_{14}o.

The beginning and the end of the winding of the choke Ch of the filter in the position of the switch 4 are connected through these condensers with the amplifier chassis as a result of which sharp attenuation of high-frequency oscillations occurs which allows to obtain the indicated new characteristics at filter switch position 4 - 4.

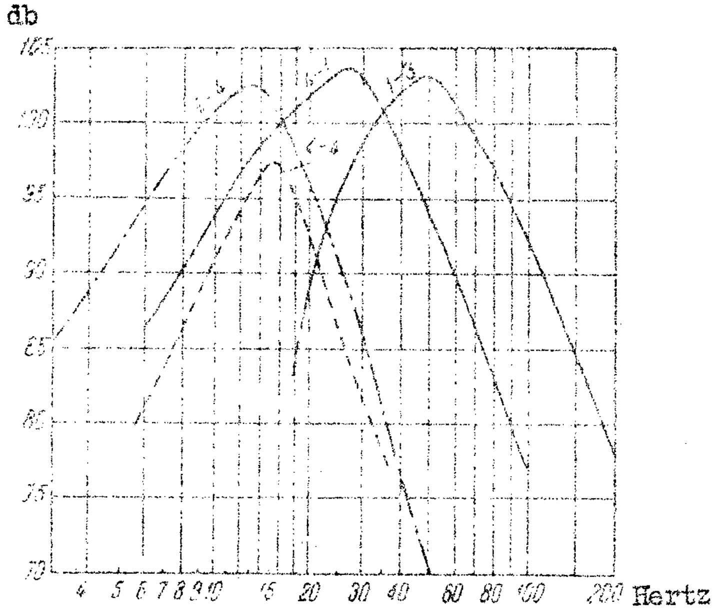


Fig. 7. Frequency characteristics of altered amplifier of the seismic station EKhO-1. The characteristics of the amplifier 4 - 4 with altered low frequency filter is shown by a dotted line. The characteristics of amplifier filtration 4 - 4 with altered filter of low frequency after exchange of condenser in the circuit primary winding of the output transformer is shown by a dotted line. The intermediate 4 - 1 and highest high-frequency 1 - 3 characteristics of amplifier with altered filter are shown by solid lines.

Widening of the bandwidth of the amplifier to the side of low frequencies. In order to widen by 10 - 15 percent the relative band width of the transmission band of the amplifier on all filtrations at the expense of shift of the low-frequency border of the characteristic into the area of lower frequencies, it is necessary to make the following changes in the diagram of the amplifier. The decoupling condensed with capacity of 0.1 microfarad included into the primary winding of the output transformer and marked on the diagram, designated C-224 on Fig. 6, should be replaced by a condenser with capacity of 0.25 microfarad. This causes broadening of the relative bandwidth of the amplifier on all filtrations by 10 - 15 percent at the expense of increase of gain at low frequencies; for example, the low-frequency border of transmission band is newly introduced low frequency characteristic on filtration 4 - 4 is shifted to 6 - 8 cycles. This characteristic is shown on Fig. 7 by broken dotted line.

In given alterations it is necessary to pay particular attention to select condensers of equal capacities. Their difference in size should not exceed 1 - 2 percent.

After modification of the low frequency filters it is necessary to check that the amplifiers are identical at altered filtration 4 - 4 and in case of need to make the amplifiers identical.

The fact that the amplifiers are identical in the whole working range of frequencies can be checked either by means of recording of sinusoidal oscillations on the oscillogram, fed simultaneously by the signal generator to the inputs of all amplifiers, connected in parallel, or by using the Lissajous patterns.

If on the record of the sinusoidal oscillations, taken usually over intervals of 5 - 6 cycles within the limits of the bandwidth of the given filtration, the relative time shifts of the extrema of the sinusoidal oscillations do not exceed 0.001 sec, then the identicity of amplifiers is satisfactory. There, naturally, the galvanometers must be identical. However, if the relative shifts for separate amplifiers are greater than 0.001 sec., then, in the modified filters of these amplifiers the capacitance should be changed in such a way that the relative shifts do not exceed 0.001 sec.

The checking of identicity of amplifiers by Lissajous patterns is performed in the following manner. A voltage of a given fixed frequency is fed to inputs of two tested amplifiers from the signal generators. The output of one generator is attached to vertical plates and output of the other to horizontal plates of the cathode ray oscillograph. If the phase shift between the amplifiers, $\Delta \varphi^o$, is equal to zero, then a straight line will be observed on the screen of cathode oscillograph. If the phase shift in not equal to zero, then an ellipse will be observed on the screen. The ratio of the minor axis of the ellipse B to the major axis A will characterize the size of the shift of phases $\Delta \varphi^o$. The value of $\Delta \varphi^o$ in case when equal voltages are fed to the plates of oscillograph is determined from the following formula:

$$\Delta \varphi^o = 2 \text{ arc tg } \frac{B}{A} \tag{4}$$

In order for the temporary phase shift not to exceed 0.001 sec., it is necessary that $\Delta \varphi^o \leqslant 0.36$ f, where f is the frequency of introduced sinusoidal oscillations. The determination of $\Delta \varphi^o$ is performed within the limits of the whole bandwidth of the given filtration with intervals of 5 - 10 cycles. If the phase shift of an individual amplifier exceeds the permissible value within the limits of the given band then in the modified filters the capacities should be changed, selecting them in such a way that $\Delta \varphi^o \leqslant 0.36$ f.

After checking the identicity of amplifiers by the Lissajous patterns a control oscillogram should also be taken by the method

described above.

The testing and adjustment of other links of seismoreceiving equipment (seismographs, galvanometers), as well as of the channel as a whole, are performed in the usual manner.

Increase of gain of the amplifiers. The gain of the amplifiers at the resonance of modified filter 4 - 4 at normal plate voltages is equal to 50, 000 (94 db). It is 1.5 - 2 times smaller than at filtrations 1 - 1, 2 - 2 and 3 - 3. To increase the gain at filtration 4 - 4 to 70,000 (to 97 db) and at other filtrations approximately to double the value, the plate voltages should be increased to 200 v.

If it is necessary to increase considerably the gain of the amplifiers, an additional stage voltage amplification should be introduced. This is done without adding new tubes and parts to the amplifier.. The triode part of the tube 6G7 is utilized for this, which is located in the ACG stage which is disconnected when working with the CMRW, as well as the components which are a part of this stage. The connection diagram of the triode part of the tube 6G7 used as an voltage amplifier is shown in Fig. 6. This stage is included in the amplifier as an intermediate third stage past the low frequency filter. This stage increases gain of the amplifier by 15 - 20 times when the plate voltage is increased to 200 v.

However, such a large gain is used in very rare cases. Therefore the total gain of the amplifier should be limited to the value of the order 150 - 300 thousand. This is done with a potentiometer connected in the grid circuit of the 6G7 tube (R-212 in Fig. 6) and located on the front panel of the amplifier under the slot. After the modification, the stability of the amplifiers remains practically the same.

To connect the additional stage of amplification (altered ACG stage) it is expedient to add to the amplifier a special switch which, simultaneously with switching on of amplifying stage, connects the suppressor grid of tube 6SJ7 to the cathode.

Thus, all recommended alterations in the station do not change its basic working filtrations 1 - 1, 2 - 2, 3 - 3, 1 - 4 and 3 - 4, nor do they disturb the identicity of amplifiers at the indicated filtrations. The stations EKhO-1 with indicated alterations may be simultaneously used for work with CMRW as well as for work with the method of reflected waves.

In addition to making the above alterations in EKhO-1 stations, it is expedient to incorporate in them also the alterations described in Sec. 3 of this chapter.

B. Alterations in seismic station SS-24-48. This seismic station is designed for registration of higher-frequency oscillations than stations KEhO-1. As it is seen from the examination of characteristics of amplifiers of the station SS-24-48, shown in Fig. 8 as well as in Table 2, the bandwidth of the amplifiers

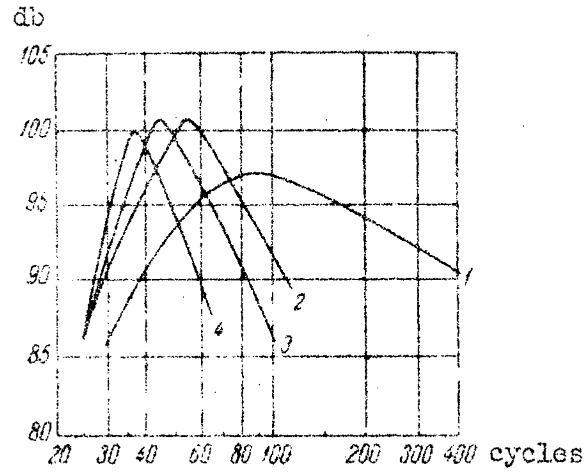


Fig. 8. The frequency characteristics of the amplifier of the seismic station SS-24-48.

is somewhat smaller than in the amplifiers of the Station EKhO-1. For example, at the lowest frequency filtration 1, it accounts to only 30 percent. The sensitivity of seismoreceiving channels of this station is also small. Therefore, in order to adapt it for work with CMRW it is necessary to introduce into the amplifiers of the station additional low-frequency characteristics, to increase the bandwidth of the amplifiers at the existing filtrations and to increase the gain of the amplifiers.

Besides, it is necessary to introduce into stations additional devices, which assure fast regulation, adjustment and control of the operation of the station and its separate units. This will allow to simplify the field work, to increase its productivity, and to improve the quality of obtained field materials.

In the CMRW it is also necessary to shut off completely the automatic gain control by taking out the tube from the ACG stage. With this, the suppressor grids of tubes 6Z7 should be disconnected from the circuit of tubes 6Kh6 and connected to the cathodes of 6Z7 tubes. It is also necessary to disconnect the mixer.

Introduction of additional low frequency characteristics. These characteristics are introduced in the amplifiers by means of replacing the intermediate coupling 0.01-mf condensers in the second and third stages which by 0.1 mf condensers and by replacing the interchangeable 240-henry choke of the filter with a 1,000-henry choke; this changes the filter resonance frequencies from 37, 43, 57 and 80 cycles to 18, 20, 25 and 35 cycles respectively.

The relative bandwidth of noes assumes the values indicated in Table 2.

Table 2.

Filtration	Resonant Frequency in cycles	Relative Band-width, in percent
1	35	130
2	25	90
3	20	70
4	18	45

In those cases, when it is necessary to register oscillations with predominant frequencies over 40 cycles the 240 henry choke should be used. The resonant frequencies of the filters will then be 37, 43, 57 and 80 cycles, i.e., the same as in unaltered station. However, this increases the relative bandwidth insignificantly (by 10 percent) compared with the bandwidth of unaltered amplifiers. The broadening of the amplifiers bandwidth is shown in Table 3.

Table 3.

Filtration	Resonant Frequency Cycles	Relative bandwidth	
		Unaltered amplifiers	Altered amplifiers
1	80	--	--
2	57	50	60
3	48	40	50
4	37	30	40

The characteristics of amplifiers after alterations are shown in Fig. 9. Here, the solid lines indicate the characteristics when a new choke of inductance $L_1 = 1,000$ henry is included in the filter; by dotted line indicates the characteristics for the case when the old choke of $L = 240$ henry in used.

Increasing the gain of the amplifiers. The increase may be realized at the expense of switching off of the 6Kh6 tube in the AGC circuit;by replacing the 0.01 mf condensers C_1 and C_2 in the second and third stage by 0.01 mfd condensers; and by increasing the plate voltage to 140 v.

The indicated measures assure the increase gain of the voltage amplifiers to 180,000, i.e., 106 db at the primary winding of output transformer. Further increase of the gain of the amplifier may be reached to some degree by increase of voltage of anode batteries to 200 v.

Apparatus for rapid control of the operation of the individual units of the station. In the station SS-24-48, unlike the station EKhO-1, there are no linear input units.

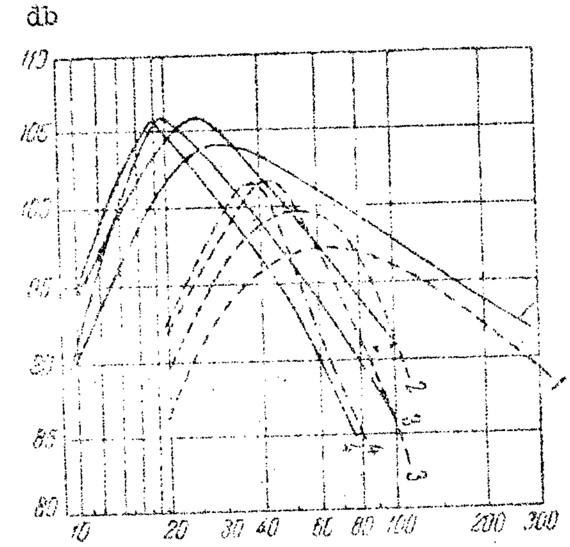


Fig. 9. Frequency characteristics of seismic station SS-24-48. The characteristics with the 1000-henry choke are shown by solid lines; and those with the 240-henry (old) choke are shown dotted.

Therefore for realization, in the process of operation of fast control of the operation of the channel and its separate links in the station, it is necessary to make a checking panel, which would allow by simple switching to: a) check the conductivity of the lines to the seismographs; b) to connect in parallel the inputs of all amplifiers, as is necessary in taking recording for identicity; c) to attach to the input of all amplifiers a signal generator to set the amplifiers for equal sensitivity.

It is also necessary to foresee the possibility of attaching the output circuit of any amplifier to the oscilloscope for checking the operation and identicity of the amplifier.

Thus, the alterations in the station practically do not change the working filtrations of channels 1, 2, 3, 4, and also do not disrupt the identicity of amplifiers. Therefore the station SS-24-48 with indicated alterations may be used simultaneously for work with CMRW as well as for work according to the method of reflected waves.

C. Modification pertaining to the stations EKhO-1 and SS-24-48, which simplify the performance of field observations and contribute to better quality of obtained field materials. Aside from the alterations in amplifiers of both stations indicated previously, the carbon potentiometers, which regulate smoothly the gain of

amplifiers should be replaced by calibrated step-by-step ones, which change the sensitivity by a certain factor.

It is also necessary to assure the possibility of equal simultaneous change of sensitivity of all channels. This, for example, may be realized by regulation of voltage on the screen grids of tubes of first or second stages of amplifiers. The feeding of screen grids in this case should be performed from a separate battery. As experience shows, such a method of regulation of sensitivity of amplifiers practically does not introduce any relative complications (distortion) into seismic recordings.

In order to decrease the filtration of the channel, it is desirable to lower also seismographs' own sensitivity to 10 - 12 cycles, but to do this without loss for stable operation in the available types of magnetic seismographs for example SP-48, SP-12 and others, is extremely difficult, since in this the danger of "sticking" of the moving system of the apparatus increases.

In the future it is expedient to utilize in the CMRW electrodynamic seismographs, in which it is easy to assure low natural frequency of the order of 10 - 12 cycles and which are more stable in work than the above mentioned magnetic seismographs.

The transition to registration of lower low frequency oscillations allows to decrease the speed of the paper to 14 - 20 cm/sec. This is achieved by means of decrease of feeding voltage of the chart motor from 12 to 9 - 8 v.

It is necessary for all stations which are destined for work with CMRW to add a signal generator (preferably with expanded scale in the frequency from 5 - 10 to 100 cycle) and a cathode ray oscillograph.

3. Introduction of Calibrated Sensitivity of Seismic Receiving Channels.

In order to utilize the dynamic peculiarities of seismic recordings in interpretation, it is necessary, as shown in Sec. 1, Chapter IV, to introduce calibrated sensitivity of seismic receiving channels. For this it is necessary to know either the relative sensitivity of seismic receiving channels or to perform registration of oscillations at equal sensitivity. The above may be realized in the following manner:

1) introduce in the amplifiers a step-by-step calibrated sensitivity control, simultaneously selecting seismographs and galvanometers of equal sensitivity for all channels;

2) fix before each explosion the relative sensitivity of seismoreceiving channels (without seismographs, simultaneously selecting seismographs of equal sensitivity for all channels.

The step-by-step calibrated sensitivity control of the amplifiers may be realized in the following manner. The carbon potentiometers, which regulate smoothly the sensitivity of amplifiers, are replaced by step-by-step potentiometers, which change the sensitivity by a certain factor. As experience shows, in the presence of possibility of simultaneous smooth regulation

of sensitivity of all channels, it is sufficient to introduce five stages of sensitivity control, and in switching from one stage to the other, the sensitivity should at least double.

The step potentiometers used for this are usual multiple contact switches with a corresponding set of resistors. Standard low-power resitors can be utilized as resitors.

In presence of amplifiers with calibrated regulation of sensitivity, it is easy to record at equal sensitivity of channels for which purpose the switches of potentiometers of amplifiers must be placed into same position, as well as at unequal, but known sensitivity of channels. In the latter case it is sufficient to only fix the positions of the switches of amplifier potentiometers which regulate the sensitivity.

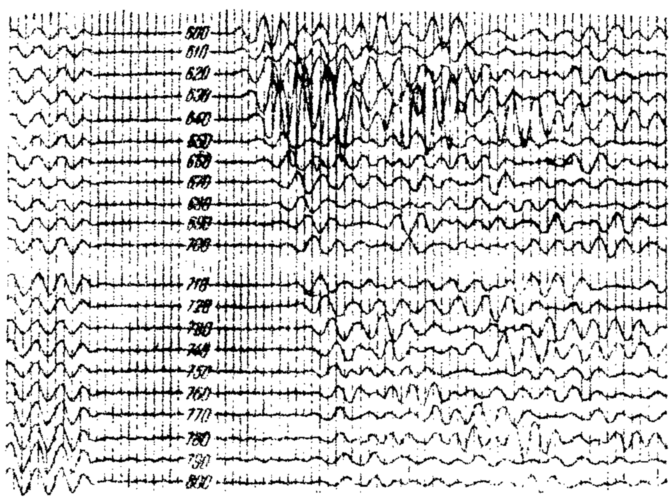


Fig. 10. Seismogram, which shows on the left in the initial part, the recording of sinusoidal oscillations generated by the signal generator at the inputs of all amplifiers. The amplitude ratio of these oscillations charactises the relative sensitivity of receiving channels without seismographs.

The relative sensitivity of channels (without seismograph) in production of records, when the amplifiers do not have the step-calibrated regulation, may be fixed in the following manner. Before the explosion, sinusoidal oscillations with frequency close to the frequency of waves being registered are fed from the signal generator to the inputs of all amplifiers for a short period of time, 0.1 - 0.3 sec. These oscillations, as is seen on the seismogram shown in Fig. 10 are recorded in its initial part before the arrival of seismic waves. According to such recording it is possible to determine the correlation between the sensitivity of various channels. This allows in the processing to introduce corresponding corrections into the amplitude measurements, due to unequal

sensitivity of channels.

Using the signal generator, it is also possible to set all channels at equal sensitivity.

Before the explosion, the signal generator is connected to the circuit of the amplifier at identical input transformers and first stages in the following manner: the secondary winding of the signal generator is connected in series with the anode battery, which feeds the anodes of tubes of the first stages of amplifiers (which are connected in parallel).

Thus, a voltage of a given fixed frequency is applied to the grids of tubes of second stages of all amplifiers from the signal generator. When the chart in started the circuit of the secondary winding of the audio generator is short circuited automatically or semi-automatically after 0.2 - 0.3 sec, and this stops completely the supply of voltage from the sould generator to the grids.

4. Radio communication and determination of the instat of explosion by radio.

Radio communication. In work with CMRW, the explosions occur at great distance from the seismic stations, on the order of 5 - 10 km. and more. Therefore, in conducting field work radio communication is utilized for communication between the explosion points and the seismic stations and for transmission of the instat of explosion.

For radio communication, the seismic station is usually equipped with a set of four radio stations, and the radio stations which service the explosion points are equipped with devices that produce an electric impulse that corresponds to the moment of explosion.

At the present time, for use in seismological engineering, the radio stations manufactured by our industry, of the type "Urozhay" [29], destined for one-sided (simples) as well as simultaneous two-sided (duplex) communication on distances of up to 30 km, and quite suitable. These stations are simple in arrangement, portable and reliable in operation. The simplicity of operation of radio stations enables the personnel of the seismic groups to operate them.

In those cases, when the length of profiles exceeds the range of radio stations of the type "Urozhay", more powerful radio stations should be used, or one should place between the seismic station and the point of explosion additional intermediate retransmitting radio stations.

Marking of the moment of explosion. For marking of the moment of explosion on radio, the following methods are utilized in practice:

1) the marking of the moment of explosion by means of recording on the seismogram of the electric impulse which corresponds to the moment of explosion;

2) the marking of the moment of explosion by means of

recording on the seismogram of suddenly terminating or suddenly starting sinusoidal oscillations of the sound frequency. In this case either termination or starting of recording of sinusiodal oscillations corresponds to the moment of explosion.

Marking of the moment of explosion by means of recording of the impulse. For marking the moment of explosion by a pulse, one uses the usual explosion devices (see for example, 58) and other explosion devices (explosion commutator, etc.), allowed for use in seismic engineering by the Mining Engineer Inspection Service and equipped with devices for production and transmission by telephone lines of the electric ipulse, which corresponds to the moment of explosion. In case of utilization of the explosive machine, the transmission of the moment of explosion on radio is realized in the following manner. The secondary winding III of the transformer of the machine (Fig. 11) is connected to the primary winding of the microphone transformer, either instead of the microphone or else to the circuit of additional winding, which serves usually for re-transmission.

Fig. 11 illustrates the marking the moment of explosion by radio in case of utilization of the explosion machine and of a radio station of the type "Urozhay-1" (b) [29]. At the moment of explosion the circuit of electric detonator opens and a sharp electric pulse is produced in winding I of the transformer of the machine. This pulse is then fed to the winding of the microphone transformer of the radio station and is broadcast.

The impulse is received by the radio receiver through the decoupling filter whose diagram is shown in Fig. 12, is fed to one

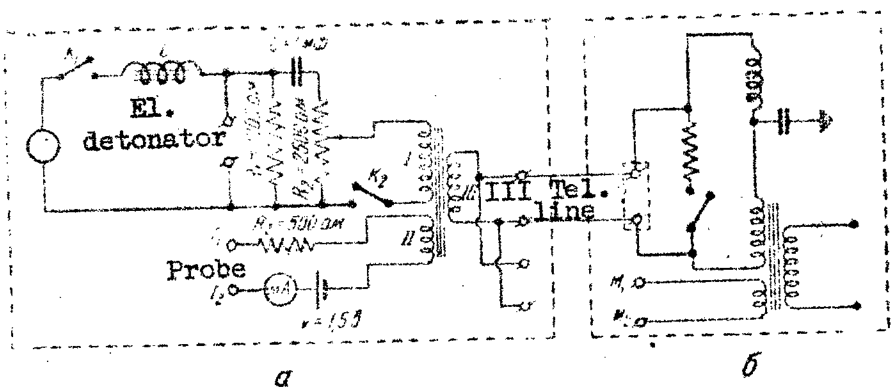


Fig. 11. Connects diagram of the transformer of the explosive machine used in marking of the moment of explosion by radio, by means of recording of the electric pulse on the seismogram.
a - explosive machine; b - microphone transformer of the radio station "Urozhay-1".

of the galvanometers and is recorded on the seismogram. This galvanometer is utilized also for recording of seismic oscillations. The decoupling filter is included in the circuit of the galvanometer in order to decouple the circuits of the amplifier and radio station

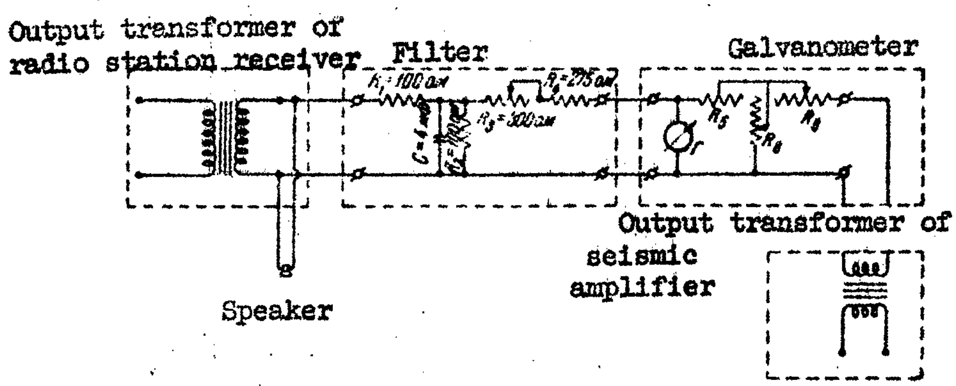


Fig. 12. The connecting diagram of the receiver of the radio-station to the galvanometer (through decoupling filter), used to mark the moment of explosion by means of recording of the electric impulse on the seismogram. The parameters, indicated in the diagram, refer to that case when the input resistance of the galvanometer equal 20 Ohm.

and to eliminate the effect of speech and various types of atmospheric interferences on the galvanometer.

An example of a seismogram with the moment of explosion marked by recording of a pulse is shown in Fig. 64. The timing line is tested before the explosion by closing and opening of the test circuit of the explosing machine.

Usual explosive commutators and test circuits of explosive machines may also be utilized for marking the moment of explosion by means of recording an electric pulse on the seismogram. In the given case an additional two-wire time line is included into the circuit of the primary winding of the transformer of the explosive commutator, a turn of this line is wound on the charge. At the moment of explosion the turn is broken and, consequently, the circuit of the timing line is broken. This cause a momentary cessation of the current in the circuit of the timing line and is noted on the seismogram as a pulse.

The marking of the moment of explosion in the form of a pulse can be also performed in the following manner. The timing line, which has small resistance as compared with the resistance of the microphone, is connected in parallel with the microphone. At the moment of explosion the current in the primary winding of the

transformer decreases sharply. This decrease of the current, received by the receiving station, is recorded on the seismogram as a pulse.

If the resistance of the timing line cannot be made small compared with the resistance of the microphone, then the line should be switched in series with the microphone.

The separate timing line should in all cases be connected through an explosive commutator equipped with safety switches.

A circuit with a separate line is best used in those cases, when the poor quality of the electric detonators or some other reasons cause the detonation of the charge to be noticeably delayed with respect to the opening of the explosion circuit, i.e., with respect to the moment of burning out of the bridge of electric detonator. However, if there is no delay, than it is simpler and easier to utilize a circuit with an explosive machine for marking the moment of explosion.

Marking of the moment of explosion by recording on the seismogram suddenly stopped or suddenly beginning sinusiodal oscillations. The marking of the moment of explosion by means of recording of suddenly stopping sinusiodal oscillations is realized by means of the circuit of Fig. 13. In this case a sound generator (the secondary winding of its output transformer) is connected to the circuit of the separate timing line, which is connected in series with the primary winding of the microphone transformer of the radio stations. Due to this, the carrier frequency of the transmitter is modulated by sinusiodal oscillations, whose frequency usually does not exceed 200 - 300 cycles. At the moment of explosion the moment line is broken, and this stops the modulation of the carrier frequency of the transmitter by the sinusiodal oscillations.

The termination of sinusiodal oscillations is recorded on the seismogram in the same manner as the marking of the moment of explosion by pulse. An example of a seismogram with marking of the moment of explosion by means of registration of suddenly terminating sinusiodal oscillations is shown on Fig. 14. In some cases the sidusiodal oscillations received by the receiving sradio station are first rectified and then fed to the galvanometer. The moment of explosion in this area is marked on the seismogram as a shift in the path of the light. For rectification, either tube circuits or circuits with copper oxide rectifiers are used.

The marking of the moment by means of recording of suddenly starting sinusiodal oscillations may be realized by means of the following modification of the circuit with a sound generator. In the circuit shown on Fig. 13, the secondary winding of the sound generator is connected directly to the primary winding of the microphone transformer. The timing line is connected to the same circuit, thereby completely shuting the winding of the generator. This stops the modulation of the carrying frequency of the transmitter by sinusiodal oscillations. At the moment of explosion

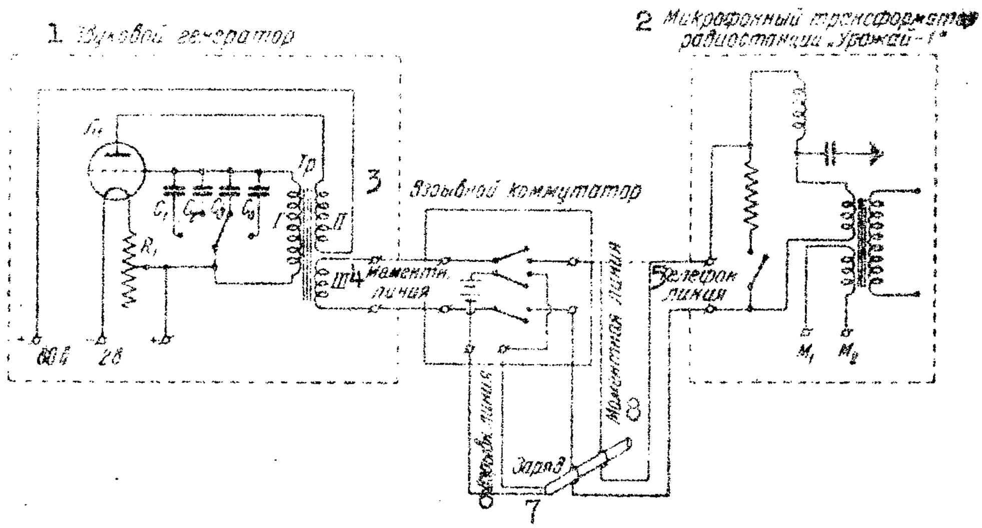


Fig. 13. The diagram of marking the moment of explosion on radio by means of recording of suddenly terminating sinusiodal oscillations. Termination of sinusiodal oscillations corresponds to the moment of explosion. 1 - sound generator; 2 - microphone transformer of radio station "Urozhay-1"; 3 - Explosive commutator; 4 - timing line; 5 - telephone line; 6 - expl. line; 7 - charge; 8 - time line.

the turn of the timing line is broken, the generator winding is no longer shunted and modulation of the carrier frequency of the transmitter with sinusiodal oscillations is resumed. In order to obtain in such a circuit sufficiently sharp sinusiodal oscillations on the seismogram it is necessary that the resistance of the timing line, before it is broken, be small, about several ohm, and that its resistance after the break be sufficiently large.

In those cases when the resistance of the timing line after the breaking of the wires remains small, about several ohms, as takes place, for example, in explosions in salt water, the circuits described above cannot ensure the production of a sufficiently sharply pronounced start of sinusoidal oscillation. The sharpness of the start of the oscillations can be increased by modifying the circuit shown in Fig. 13 in the following manner. Winding I of the transformer Tr (Fig. 15) is coupled inductively with the plate circuit not directly bthrough winding II, but through an additional network, which has low resistance, several ohms. The resistance of the network can be increased if necessary, by adding the resistance R. Connected in parallel with this network is a timing line, which shuts it completely. At the instant of explosion the

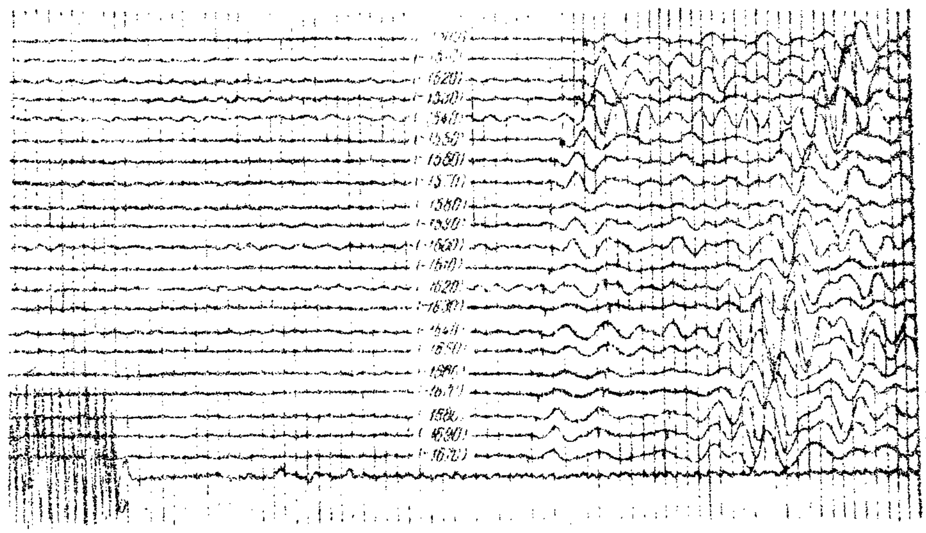


Fig. 14. Example of seismogram with radio recording of the instant of explosion to which the termination of sinusiodal oscillations corresponds.

shunting ceases and the modulation of the carrier frequency of the transmitter begins. Such a circuit can be adjusted to operate whenever the resistance in the timing line increase by several ohms.

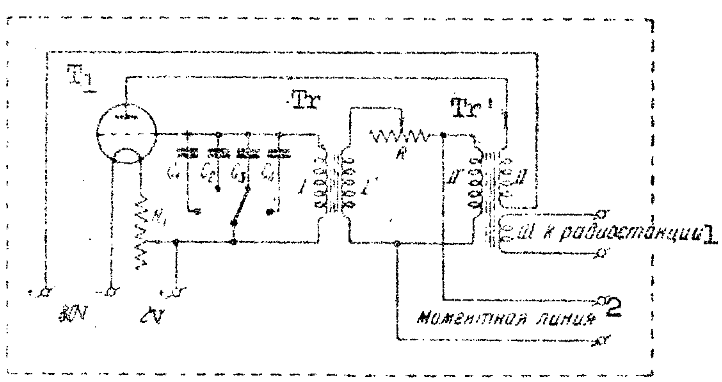


Fig. 15. Diagram of audio generator, used to mark the instant of explosion by radio by recording the instantaneously starting sinusoidal oscillations in the case of explosions in salt water. 1) to radio station; 2) timing line

Methods of marking the instant of explosion by recording suddenly stopping or suddenly starting sinusoidal oscillations ensures a clear-cut marking of the instant of explosion in the presence of strong thunderstorm discharges or interference due to neighboring operating radio stations. In this lies their advantage over time marking with the aid of pulse recording. However, if this interference is missing, then when operating with modern radio stations, particularly at short distances on the order of several kilometers, preference should be given to time marking by means of pulse recording.

Non-coincidence between the instants of explosion in the case of repeated explosions. If an additional timing line is used, in the case of explosions in water-filled shot holes, and also in the case of explosions in natural water reservoir and particularly at sea, one frequently observes an apparent discrepancy between the times of arrivals of the same waves in the case of repeated explosions made with the same setup. These discrepancies sometimes reach 0.005 -- 0.006 seconds and more. They may be caused by inexact recording of the instant of explosion by means of the ordinary circuits, owing to small variations in the resistance of the timing line after the breaking of the wires.

The sharpness of the arrivals of the pulse, corresponding to the instant of explosion, can be increased in the following manner. The charge is wrapped not with a single wire of the timing line, as is usually done in ordinary schemes (the connection of the wires of the timing line is shown for this case by the dotted line of Fig. 13), but with two wires, so that four wires of the timing line enter into the shot hole (the corresponding connection of the timing-line wires is shown by the solid lines in Fig. 13). With such a connection between the test lead or the sound generator and the circuit of the microphone transformer of the radio station, the radio station is always disconnected completely during the instant of explosion from the circuits that make up the electric pulse corresponding to the instant of explosion, and this results in a sharper recording of the instant of explosion. In addition, this eliminates almost completely the possibility of appearance of overshoots on the seismogram. These overshoot usually are due to repeated closing of the wires of the timing line.

In the case of explosions in dry wells, on the surface, and in air, a satisfactory agreement between the instants is obtained also with the usual method of connection of the timing loop. The occasionally observed non-coincidence of the times of each arrivals is due to other causes: in the case of explosions in mountain rocks -- to crumbling (and sometimes packing) of the rocks near the explosion and the related changes in the conditions of absorption and speed of propagation of elastic oscillations. In the case of explosions in air -- this is due to the dependence

of the velocity of the explosion wave in air on the size of the charge, etc.

The foregoing circumstances, which influence the accuracy of marking of the instant of explosion by radio, occur also when working with wire lines.

CHAPTER III

PROCEDURE OF FIELD OBSERVATIONS

The procedure of field observations in the CMRW differs from the method of reflected waves in the great variety of observation systems. Whereas in the method of reflections use is made principally of longitudinal profiles, in the CMRW, along with longitudinal profiles, one uses extensively non-longitudinal and different combinations of longitudinal and non-longitudinal profiles.

The method of shooting the longitudinal profiles themselves is more complicated in CMRW than in the method of reflection. This is connected with the fact that the reflacted waves, unlike the reflected ones, cannot be observed near the point of explosion, but only starting with a certain distance, which sometimes is quite considerable. In addition, to construct refracting separation boundaries it is necessary to have a system of observations from not less than two explosion points. Therefore the simplest system of shooting longitudinal profiles used in the reflected wave method is quite inapplicable in the CMRW.

In the CMRW, as in the method of reflections, use is made of various types of measurement -- route and area. The choice of type of measurement and the system of observations are determined by the character of the prospecting problems that are to be solved by the CMRW. In scheduling CMRW operations, as in the method of reflections, a tentative scheme of observations is first outlined, based on general data on the geological structure of the region or the regions adjacent to it, and using the experience of seismic prospecting in neighboring regions or under similar conditions. Finally the observation scheme is selected on the basis of result of experimental works, during which one obtains the basic information on the bearing refracting horizons: their approximate depths, the magnitudes of the boundary velocities, and the regions in which the waves can be traced. During the time of the experimental operations, one clarifies also the technical problems connected principally with conditions of excitation of oscillations (and to a lesser extent with the conditions of mounting the seismographs) in choosing the locations of the seismic profiles.

When using the CMRW, as in the use of the method of reflected waves, it becomes sometimes necessary during the

operating procedure to deviate from the previously outlined scheme of observation in order to obtain such a network of observation of the material. Most frequently it becomes necessary to complicate the system of observations, particularly in those places where unpredicted complex seismological conditions are encountered.

1. Types of Measurements

One distinguishes two principal types of seismic measurements, carried out with the aid of the CMRW: route and area.

Route measurement. This type of measurement presupposes the performance of operations along individual lines -- routes -- for the study of the geological section. Use is made here essentially of isolated longitudinal profiles, sometimes in conjunction with transverse ones. As a result of such measurement, seismic sections are plotted along the lines of the profiles.

Area measurement. This system of observations represents in this case a definite network of profiles. Area measurement can be carried out in order to search for structures or in order to make a detailed investigation of structures already known. In this connection one distinguishes between reconnaissance or search area measurement, in detailed area measurement. In either case one use in principle the same systems of observations, but in detailed measurements one uses a greater density of network of profiles and they are shot in greater detail.

As a result of carrying out the area measurements structural maps are plotted, the routes of lines of tectonic disturbances (faults, steep slopes) are traced, and seismological maps are compiled for the extent of various rocks under covering layers. Structural and other maps are usually accompanied by seismic sections along the most characteristic profiles.

2. Principal Systems of Observation

The principal systems of observations in CMRW are longitudinal and non-longitudinal profiles, which are distinguished from each other by the mutual placement of the points of explosion and of the seismographs. In any system of observations, the seismographs are usually arranged along straight lines -- profiles.

Longitudinal profiles. In the CMRW one calls longitudinal profiles such systems of observations, in which

the seismographs and the point of explosion are located on the single straight line (Fig. 16). Longitudinal profiles represent basic, or as they are also called, reference profiles, since a sufficiently complete system of hodographs, obtained with these profiles makes it possible to determine the depth and relief of the refracting boundary, and also the magnitude of the boundary velocity.

Other lines of observations are for the most part related in one manner or another with longitudinal profiles.

Non-longitudinal profiles. Non-longitudinal profiles are called such systems of observations in which the point of explosion in the line on which the seismographs are placed are not on a straight line. Frequent and most widely used cases of non-longitudinal profiles employed in practice are transverse profiles. A non-longitudinal profile is called transverse if the base of a perpendicular dropped from the point of explosion on to the profile line is located in the same profile, and not on its continuation (Fig. 17, CC'). Non-longitudinal profiles, located on the side of the base of the perpendicular, are sometimes also called lateral (Fig. 17, DD'). It must be borne in mind that the separation of non-longitudinal profiles into transverse and lateral is purely arbitrary in character, since the procedure of shooting these profiles and method of interpreting the hodographs, obtained on transverse and lateral profiles, are as a rule the same. Exceptions are portions of non-longitudinal profiles (lateral or transverse) which are remote from the point of explosion, and which under certain assumptions can be interpreted as longitudinal profiles.. In those cases when the point of explosion is a longitudinal profile, the transverse profiles are arranged perpendicular relative to the longitudinal one (Fig. 17, BB').

Non-longitudinal profiles represent a system of observations, which makes it possible to determine only the relative depths of the refracting boundary -- its relief. In those cases when the observations of longitudinal profiles are connected in some manner or another with the observations on longitudinal profiles, where the system of observations makes it possible to determine the absolute depths, they permit a determination of also the absolute depth of location of the separation boundary.

Non-longitudinal profiles are usually an important element of area measurement. Most frequently they are used in conjunction with longitudinal profiles. But in solving reconnaissance problems, in those cases when it becomes necessary to determine only qualitative elements

of the structure -- to trace the axis of the uplift, the fault line, or a steep descent of a boundary, then isolated non-longitudinal (most frequently transverse) profiles are sometimes used, which under favorable conditions make it possible to solve such problems rapidly with relatively little work.

Combinations of longitudinal and non-longitudinal profiles. Various combinations of longitudinal and non-longitudinal profiles are widely used, and make it possible to determine the spatial distribution of refracting boundaries. These include primarily various "crosses" of profiles, for example longitudinal and transverse (Fig. 18A), two non-longitudinal (lateral and transverse))Fig. 18B), non-longitudinal (lateral) and longitudinal (Fig. 18C).

In area measurement one uses various nets of profiles: a network of longitudinal profiles, a network of non-longitudinal profiles, and a network of profiles consisting of a combined system of longitudinal and non-longitudinal profiles. The systems of observations used in area measurement are considered in greater detail in Section 5 of this chapter.

3. Systems of Observations on Longitudinal Profiles

Systems of observations on longitudinal profiles, designed for tracing waves, corresponding to a definite boundary, can represent so-called "complete" or "incomplete" correlation systems of observations. When prospecting simultaneously several refracting boundaries, the same system can be complete with respect to waves corresponding to any one or several of the investigated boundaries and incomplete with respect to others.

Complete correlation systems of observations. By complete correlation systems of observations we mean such a system, which in the case of continuous separation boundary makes it possible to realize along the entire profile a continuous correlation of the phases of the waves corresponding to this boundary. The identification of the phases of the waves are followed at different points of explosion as realized by mutual points.

Incomplete correlation system of observations. In contrast with the complete correlation system of observations, the incomplete system of observations does not insure continuous tracing of the waves by phases, fully interrelated by mutual points. The identification and the interrelation of the waves in this type of system is

realized not only by mutual points, but also by the principle of the parallelness of overtaking hodographs, by features of the type of recording, etc. Thus, the system of overtaking hodographs, not interrelated by mutual points, represents an example of an incomplete correlation system of observations.

Compilation of correlation observation schemes. In order to realize a correlation interrelation of the phases of the waves which are followed from different points of the explosion, it is necessary to locate these points suitably on the profile and to determine the shooting intervals for each of these points. To determine the mutual placement of the points of explosion and the shooting intervals it is convenient to use the so-called "generalized plane of observations."

The concept of generalized plane of observation makes it possible to penetrate deeper into the question of the analysis of seismic fields at different systems of observations /21/. Here we use the generalized plane only for purposes of representing the scheme of correlation system of observations on a longitudinal profile. The compilation of correlation schemes in the CMRW plays a substantial role in the scheduling and carrying out the operations, particularly in those cases when it is necessary to follow simultaneously several separation boundaries.

The method of compiling the correlation scheme on a generalized plane of observations would be clarified with the aid of the following example. Assume that we have a complete correlation system of observations, represented by a system of opposite hodographs, as indicated in Fig. 19. To represent this system on the generalized plane of observations we perform the following operations. We take the horizontal axis x (Fig. 20) and mark on it the stations of the longitudinal profile. Through the end station of the horizontal axis we draw a vertical axis y, on which we also mark the stations, where station 1 of the vertical axis is taken to be station 6 of the horizontal axis. We then join station 1 of the horizontal axis and station 6 of the vertical axis with a straight line. We obtain the hypothenuse of a right triangle, the sides of which are equal to the length of the longitudinal profile. The plane of the triangle will indeed be the generalized plane of observations. The explosion points (EP) O_1, O_2, O_3, ... on Fig. 19 correspond on the generalized plane (Fig. 20) to the points on the hypothenuse of the triangle, denoted by the same letters.

The horizontal lines drawn form the points O_1, O_2,

O_3 (Fig. 20), correspond to the direct tracks on the profile, i.e., those at which the seismographs are located to the right of the point of explosion (and the direction of increasing station numbers), while the vertical ones will correspond to the reverse path, i.e., such at which the seismographs are located to the left of the point of explosion. For example, if on the profile (Fig. 19) a direct path is followed and hodographs E'F is obtained from explosion point O_3, then the corresponding section on the generalized plane is EF, which is on the horizontal line O_3F, passing through the point of explosion O_3; corresponding to the reverse path from this point of explosion O_3, covered in the interval of the profile between the points of explosions O_2 and O_1 (Fig. 19) corresponds on the generalized plane to the section CB on the vertical line O_3B (Fig. 20).

From a comparison of Figs. 19 and 20 it is seen that the mutual points of the hodographs, for example B and B' (Fig. 19), merge on the generalized plane in a single point B (Fig. 20); analogously, to two points C and C' (Fig. 19) there corresponds point C and Fig. 20. This leads to a great simplification and great clarity in the graphic representation of complex paths in the continuous correlation interrelation of observations on longitudinal profiles; the looped complex path ABD'CC'DD' on Fig. 19 becomes in a simple broken line ABCD and Fig. 20.

The overtaking hodographs are represented on the generalized plane by parallel horizontal or vertical straight lines, which have a region of overlap, for example the lines Ff and Gh, HR' and GF on Fig. 20.

We note that when represented on the generalized plane, the simplest correlation scheme of observation by the method of reflections is given by a broken line of the form $Q_1AO_2CO_3$..., where in pairs of mutual points on the hodograph corrrespond in this case to the points ACE..., and the points O_1O_2 and O_3 ..., correspond to observations at which the point of explosion and the point of location of the seismography coincide.

The simplest correlation scheme of observations along the profile for the CMRW, as can be seen from Fig. 20, represents a continuous broken line ABCD..., removed from the hypothenuse O_1 -- O_6 and located in the region where the refracted wave can be traced; the region of tracing on the generalized plane, in the case of a horizontal separation boundary, is bounded between the lines PP' and RR', parallel to the hypothenuse of the triangle.

The distance O_1P equals twice the magnitude of the drift (see formula (1.1)).

Examples of complete correlation systems of observations for the case of a single separation boundary. The system of observations given above (Figs. 19 and 20) represents one of the cases of complete correlation system of observations for tracing waves, corresponding to a single separation boundary. In spite of the fact that this is a complete system, it has its shortcomings: there are no overtaking hodographs here. Therefore this system can be recommended only in those cases, when the waves corresponding to the prospected separation boundary have pronounced dynamic differences from other waves and their recognition involves no difficulty. In the opposite case the interrelation of the waves only by mutual points will not always be reliable, owing to the possibility of certain errors in the correlation when tracing waves on opposite systems of observations; for example, the changeover from phases of one wave to phases of another wave in the zone of their interference. In addition, it is necessary to bear in mind that in some cases even in the presence of a fully interrelated correlation system of observations, it becomes impossible to construct a continuous separation boundary along the entire line of the profile. In contradiction to the method of reflected waves, in which continuous tracing of the wave insures the construction of the continuous separation boundary, in the method of refraction the continuous correlation does not always correspond to a continuous tracing of the separation boundary (Fig. 21). For shallow separation boundaries a continuous tracing of the refracting boundary is ensured by a system of opposite hodographs, which have overlapping regions. For deep boundaries, in view of the great magnitude of the drifts, this condition is not always mandatory when $h \gg H$, as can be seen from Fig. 21.

To obtain opposing summary hodographs with a considerable overlap region it is necessary to supplement the system of opposing hodographs with overtaking ones. Figs. 22 and 23 show two versions of complete correlation systems of observations, insuring the production of opposing and overtaking hodographs.

In the former case (Fig. 22) the system of observations forms so-called closed paths. The correlation interrelation of the waves is realized not only with the aid of opposing but also with overtaking hodographs. This type of interrelation insures a very reliable tracing of the phases of the waves. On each interval of the profile there are overtaking straight lines and return paths. For example,

in the interval 4 -- 6 there are two straight paths AB and A'B' from explosion points O_1 and O_2, and two return paths C'C'' and DD' from explosion points O_5 and O_6, i.e., this interval of the profile is shot from four explosion points. In the interval 6 -- 8 there are two direct paths B'C and B''C' from explosion points O_2 and O_3 and one return path D'D'' from explosion point O_6, etc.

The second case (Fig. 23) represents a system of observations that insures the production of overtaking hodographs without the use of closed paths. Here the regions of overlap of the overtaking hodographs are twice as small as in the preceding case. The correlation interrelation is realized only with opposite hodographs. The overt aking hodographs are so arranged, that at each interval there is only one direct or reverse path. Thus, in the profile interval 6 -- 8 or CC 6 -- 7 there is a straight overtaking path AA', and on CC 7 -- 8 there is only the direct path BB'. The maximum number of simultaneously -- operating explosion points, necessary to obtain this system, is equal to 3.

In practice in those cases when the use of closed correlation paths (Fig. 22) is not dictated by particularly difficult conditions of wave correlation, one usually employs observation systems similar to those shown in Fig. 23, since they are more economical with respect to the necessary number of simultaneously operating explosion points.

Incomplete correlation systems of observation in tracing one separation boundary. In practice it does not always make sense to require the realization of a complete correlation system of observations for waves corresponding to the principal separation boundary, and all the more for other refracting boundaries, investigated in a given region, for in many cases when the parallelness of the overtaking hodographs or the dynamic features of the waves are reliable criteria in the identification of waves, it is possible to employ successfully incomplete correlation systems of observations. Such systems usually represent isolated systems of opposite paths, interrelated with the aid of a system of overtaking paths. In the compilation of schemes of incomplete systems it is also convenient to use the method described above of representing the scheme of shooting of the profile on the generalized plane.

Let us give several examples of incomplete systems of observations.

Fig. 24 shows an incomplete correlation system of observation, represented by three isolated opposite paths; the correlation interrelation of the three opposite systems

is realized with the aid of overtaking paths AB, A'B' and CD, C'D'.

Fig. 24a shows the systems of opposite traverses, continued in both sides also with the aid of overt aking traverses, obtained from the so-called external points of explosion O_0 and O_5, located on the continuation of the profile line. Fig. 25b represents the same scheme on the hodograph plane (x, t).

In the case when dominating waves exist, for which it is possible to carry out a reliable identification of the phases of the waves and without a continuous correlation interrelation, one can use also a system of observations, shown in Fig. 26, consisting of two opposite systems, which are correlated to each other with the aid of several overtaking traverses.

Correlation system of observations in tracing several separation boundaries. Usually under real conditions one traces not one but several refracting levels. The regions where the waves can be traced, corresponding to these levels, as a rule do not coincide. In those cases it is necessary to choose such a system of observations, which would be complete from the correlation point of view for waves corresponding to the boundary that represents the boundary of greatest prospecting interest, and which would be if possible more or less complete for other boundaries, of lesser interest. Sometimes, at a small number of separation boundaries (two or three) it becomes possible to obtain completely interrelated systems of observations for all waves for the same shooting scheme of the profile. An example of such a scheme for the case of two boundaries is shown in Fig. 27. The region of traceability of the first wave in this example is located in the interval from A to B, and in the second from A' to B'. The second wave on the interval A'B will be traced in the form of succeeding waves, and in the interval BB' in the form of first waves.

In compilation of the system of observations in the case of simultaneous tracing of waves corresponding to several refracting levels, it is necessary to attempt to locate the explosion points in such a way, that the mutual points of the hodographs of the wave and the regions of overlap of the overtaking hodographs begin outside the zone of interference of the observed waves, for in this region the correlation of waves on the seismograms may not be reliable and the overtaking hodographs may not be parallel to each other.

It is necessary to prospect on one in the same profile deep and shallow separation boundaries simultaneously (for

example, when in the investigation of a deep boundary it is necessary to take account of the refraction on a non-horizontal intermediate boundary), then in tracing the shallow boundary the observations are carried out from one system of explosion points, located more densely, and in tracing the deep boundary -- from another, less dense system of points of explosion, wherein several of the explosion points, naturally, are used simultaneously in both systems. Sometimes in tracing boundaries located over a wide range of depths on one in the same profile, it becomes necessary to traverse this profile in practice not once but twice. One example of the scheme of observations for the case of investigation of shallow and deep separation boundaries is shown in Fig. 28. The system of observations for a shallow separation boundary consists here of opposite and overtaking traverses, such as to insure the construction of continuous opposite summary hodographs. The system of observations for a deep boundary consists of two opposite traverses from explosion points O_1 and O_6. It is supplemented by overtaking traverses AA' and BB' from external explosion points O_0 and O_7.

Length of longitudinal profiles. The maximum length of longitudinal profiles, intended for production of a section at a definite depth, depends on the placement of the region of traceability of the wave, corresponding to the deepest of the investigated levels, and is equal to a distance between the points of explosion, from which the opposite hodographs are obtained, interrelated by mutual points and insuring the plotting of the refracting separation boundary. In the case of weak velocity differentiation of the investigated boundaries, the length of such a profile may reach magnitudes of 10 to 15 times the depth of the location of the boundary.

Distance between seismographs. The distance between the seismographs on the longitudinal profiles should be selected in such a way, as to insure reliable continuous correlation of phases of the observed waves between two neighboring points of observations. The choice of distances between instruments depends on the frequency of the vibrations registered, on the magnitude of the apparent velocities V^* of wave propagation. In this case the maximum distance $\Delta x = TV^*/2$, where T is the predominating period of the regular waves. Experience has shown that at frequencies on the order of 20 -- 50 cycles and apparent velocities of 3 -- 4 km/sec the spacing between seismographs can be assumed to be 25 -- 50 meters; under particularly favorable conditions it may be increased to 100 meters. In an

investigation of small depths, on the order of 100--200 meters, when the frequencies employed amount to usually 50 -- 70 cycles, the spacing between seismographs should be reduced to 10 or 15 meters. It is necessary to bear in mind that under complicated geological conditions it becomes frequently necessary to develop more detailed system of observations; in these cases the spacing between seismographs may be reduced; at frequencies of 20 -- 50 cycles approximately to 15 -- 20 meters, and at frequencies 50 -- 70 cycles to 5 -- 10 meters.

Table 4 gives data on the distances between the points of explosion and the seismographs, used in work with CMRW in various regions.

Table 4

Distance between points of explosion and the seismographs

Region	Depth of prospecting	Distance between explosion points	Interval of shooting from one explosion point
		In kilometers	
Azerbaydzhan	0-5	3-5	0-8
Belorussia	0-4	3	0-10
Bashkiriya	0-2.5	2	0-12
Kuzbass	0-0.2	0.3-0.5	0-3

Region	Distances between seismographs on longitudinal profile	Distance between seismographs on transverse profiles
	In meters	
Azerbaydzhan	50-100	200-800
Belorussia	50	50*
Bashkiriya	25-50	--
Kuzbass	10-20	--

*In passing through the transverse profiles in this region, the same distances were used as in longitudinal profile. They could not be increased for technical causes. The seismic conditions have permitted an increase in these distances to 100 -- 150 meters.

Placement of longitudinal profiles. In the choice of the placement of reference longitudinal profiles, intended for carrying out complete quantitative interpretation of the hodographs -- the exact determination of the limiting velocities and the absolute depths of the layers, it is necessary to choose where possible sections with simple geological structures. Steeply dropping separation boundaries, sharp angular disagreement between layers, etc., may complicate the seismic picture and make it impossible to carry out reliable quantitative interpretation.

If the layers slope downward at considerable angles (approximately 8 -- 10° and more) such longitudinal reference profiles are best placed along the direction of the principal levels; on those sections where the geological and geophysical data give grounds for expecting sufficiently gentle arrangement of the principal refracting separation boundaries along the profile.

A study of the features of the geological structure of steep slopes, wings of periclinal endings of foldings, fault lines, etc., is carried out with the aid of the system of longitudinal (not reference) profiles, and also transverse profiles, the interpretation of data by which is partially based on results obtained from reference profiles which are traced under simpler conditions.

4. Non-longitudinal Profiles

Systems of observation with non-longitudinal profiles are considerably simpler than those with longitudinal ones. Non-longitudinal profiles are usually traced from one, two, and more rarely from several explosion points.

Placement of non-longitudinal profiles. Non-longitudinal profiles are placed in regions of traceability of waves, corresponding to the prospected refracting level. This determines the distance from the non-longitudinal profile to the point of explosion, from which this profile is shot. The optimum distance from the point of explosion to the non-longitudinal profile is determined on the basis of consideration of seismograms and hodographs, obtained on the longitudinal profile. The longitudinal-profile station, through which the non-longitudinal profile is drawn, particularly a transverse profile, is selected in the region of the most favorable ratio of the sharpness of the traceability of a given wave on the seismograms, obtained with the longitudinal profile.

If the entire scheme is developed (the network etc.) of longitudinal profiles, then all those profiles are so

placed, that they fit within the region of traceability of the wave of interest to us.

If the non-longitudinal profile or the system of such profiles are intended for tracing not one but several waves, then the places of the explosion points, from which the various waves are registered, are so chosen that the given profile or system are located in the regions of traceability of all these waves.

The most widespread form of non-longitudinal profiles, as already mentioned, are transverse profiles, i.e., those perpendicular to the lines of the longitudinal profiles. The transverse profiles make it possible to obtain clearer data at sufficiently angles of inclination of the prospected refracting layers, and therefore an attempt is made to locate them, in contradistion to the longitudinal profiles, not along the extent, but across the extent of the layers.

In investigation of deep separation boundaries it is advantageous to shoot the transverse profiles from two points of explosions, located from both sides of the profile. In connection with the existence of a seismic drift* this makes it possible to obtain, by shooting only a single transverse profile, information on the behavior of the separation boundary not along a single line, but over a certain area.

In choosing points for explosion points, from which transverse profiles are shot, it is desirable to avoid such a placement of the profile and the explosion point, as would make the refracting boundary experience a sharp drop from the point of explosion in the direction towards the points of the transverse profile. In this case the magnitude of the seismic drift reaches large values, and its determination becomes unreliable.

The placements of the non-longitudinal profiles, particularly transverse profiles, depends in this specific case on the problems which they are called upon to solve. Let us consider these problems and the corresponding methods of placement of non-longitudinal profiles.

1. Prospecting of zones adjacent to longitudinal profiles. If the non-longitudinal profiles cover a zone adjacent to longitudinal profile, they are most frequently made transverse, i.e., they are placed perpendicular to the

*Drift -- distance between horizontal projection of the points where the seismic ray leaves the refracting layer, and the point of observation of this ray on the surface of the earth.

longitudinal ones. Explosions in these cases are carried out at those points, which serve as the points of explosion in shooting the longitudinal profile.

2. Reconnaissance investigation of a given area including those sections of the area, which are located at a considerable distance from the longitudinal profiles. In solving reconnaissance problems one uses different systems of correlated profiles, shot both from one and from several explosion points. The places of location of the profiles are determined by the region of traceability of the waves of interest in the prospecting. The boundaries of this region are established in shooting the longitudinal profiles.

3. Investigations of those sections of longitudinal profiles which cannot be plotted with the aid of longitudinal shooting. In some cases the structures of the medium (large angles of inclination of refracting boundaries, steeply descending separation boundaries of different rocks in a layer under the refracting boundary, etc.), longitudinal profiles located for various causes in the direction of descent of the layers may yield complicated material, which is not amenable to interpretation. In those cases the individual sections of longitudinal profiles can be investigated in addition with the aid of transverse shooting from explosion points located on the side of the longitudinal profile.

If the transverse shooting of the sections of the longitudinal profile is carried out for purposes of determining the relief of the refracting boundary along the line of the longitudinal profile, then for the most reliable identification of the waves, which are traced by means of both the longitudinal and transverse shooting, it is necessary to provide for a corresponding correlation interrelation between the observations. The simplest method of such an interrelation is shown in Fig. 29. In this case the interrelation is realized with the aid of one interrelating profile, traced from the point of explosion, located on a longitudinal profile /21/.

4. Correlation between individual profiles and systems of observation. With the aid of non-longitudinal profiles it is most economical, from the point of view of volume of work, to correlate the individual profiles and observation systems. Examples of the use of non-longitudinal profiles for correlation between systems of observations are shown in Fig. 29 -- 31.

Fig. 30 shows an example of interrelation with the aid of non-longitudinal profiles of two longitudinal

profiles, Fig. 31 shows the interrelation of two transverse profiles, while Fig. 32 shows the interrelation between the longitudinal and transverse profiles.

The correlation between two separated sections of area measurements consists of correlation between any two profiles, which enter into the system of observations, employed in these sections.

We note that the role of the connecting longitudinal profiles is not restricted merely to the correlation between observations. These profiles are used later on in the interpretation (for construction of sections, structural maps, etc.) just as any other longitudinal profiles which are included in the general network of observations.

Length of non-longitudinal profiles. The length of a non-longitudinal profile is determined by the region of traceability of the waves. The length of a transverse profile, along which the sections are plotted, depends substantially on the angle of inclination of the separation boundary. At large inclination angles (above 10 -- 15°) it is recommended to use transverse profiles (Fig. 33), the lengths of which on both sides of the base of a perpendicular drop from the profile to the point of explosion, does not exceed the length R of this perpendicular. At small angles of inclination (less than 10 or 15°) length of the transverse profiles can in practice be as large as convenient. If it is necessary, in the case of large angles of inclination, to obtain a long transverse profile, it is recommended, with observance of the foregoing conditions, that the transverse profiles be "broken up" with increasing distance from the base of the perpendicular, as shown in Fig. 33.

<u>Distances between seismographs</u>. The distance between neighboring seismographs on longitudinal profiles is chosen on the same basis as that for longitudinal profiles. This distance should not be too large, so as to insure sufficiently reliable correlation between the waves that arrive at the neighboring seismographs, and also to insure sufficiently detailed solution of prospecting problems. At the same time, for economic reasons, this distance is made as large as possible.

In view of the specific features of the placement of the non-longitudinal and particularly transverse profiles, at which the increment and the distances from the point of explosion to the seismographs located at neighboring points of the transverse profile are as a rule less than on the longitudinal profile, the distance between neighboring seismographs, insuring reliable continuous correlation of

the phases of the waves on the transverse profile, can be increased by a factor of 2 -- 4 compared with similar distances on the longitudinal profile. Table 4, given above, contains data on the distances between seismographs and transverse profiles, used when working with CMRW in different regions.

The simplicity of the systems of observations used on longitudinal profiles and the possibility of considerably increasing the distances between the seismographs, serve as important advantages of non-longitudinal profiles compared with longitudinal ones when these are used in area measurements, particularly in the prospecting of deep separation boundaries.

5. Systems of Observations at Different Types of Seismic Measurements.

Let us consider systems of oservations with the aid of longitudinal and transverse profiles, which are used in route or area measurements to solve various geological prospecting problems.

Route measurements. In route measurements, the purpose of which is to study the geological section, longitudinal profiles are used preferable.

Depending on the length of the route, the geological structure of the region, and the necessary detail with which the investigations are to be performed, the longitudinal profiles are traced either over the entire length of the route (continuous profiling) or are located only on individual separated intervals of this line (seismic sounding).

In the case of inclined separation boundaries and large depth of the refracting horizons, longitudinal profiles are best supplemented with transverse "cross" profiles both for the determination of the true direction of the drop in the layers, as well as for supplementary clarification of the most complicated or most interesting (from the geological point of view) sections, disclosed on the longitudinal profiles.

The distance between crosses of the profiles on the longitudinal profile is dictated by the necessary degree of detail of the investigations and is in direct relationship to the angles of inclination of separation boundary encountered in the given region. If the angles of inclination at depths of two or three kilometers do not exceed 5 -- 10°, it is possible to place the "crosses" approximately every ten or 15 kilometers from each other. At large angles of inclination, the number of "crosses" must be increased.

A study of lateral inclination of separation boundaries (relative to the line of longitudinal profile) with the aid of transverse profiles is necessary not only to make up a clear representation of the elements of location of these boundaries along the route, but also in order to obtain a definite position of the surface, to which the section along the longitudinal profile is to be referred: at large lateral inclinations this surface cannot be considered a vertical surface.

The length of the transverse cross profiles in route measurement may be equal to the length of one or two spacings between seismographs.

Area measurement. In area measurement -- reconnaissance or detail -- the observations are carried out with the aid of networks of profiles. The choice of a given network of profiles and systems of observations based on such profiles depends on the character of the geological problems and on the requirements as regards details, which must be met in the prospecting.

One distinguishes among several types of profile systems, used in area measurement. Let us stop to consider them in connection with the conditions and problems of the prospecting.

1. Area prospecting with the aid of a net of longitudinal profiles. In the prospecting of small depths in regions with approximately horizontal deposition of layers (angles of inclination not more than 10 or 15°) one uses in area measurements a network of longitudinal profiles, on which are obtained correlation of observations, sufficient for the construction of seismic sections. One usually tends to create a more or less regular rectangular net of profiles, uniformly covering the entire area investigated. The interrelation of the data obtained in individual profiles is carried out during the process of interpretation, based on values of t_0 (see Chapter V) at the point of intersection of the profiles and based on the values of the boundary velocities.

The use of a system of longitudinal profiles makes it possible to compile not only the structural maps of the investigated level, but also maps of boundary velocities, which under the conditions of facial or other variability of rocks over the area may be of great interest to geologists.

2. Area measurements with the aid of a system of longitudinal and non-longitudinal profiles. In the prospecting at medium and large depths, in the case of media which are close to being horizontally stratified, and also

in seismic mapping of steeply descending layers with large velocities under not too thick a layer of loose deposits, it is advisable to use nets of profiles, consisting of a partially or completely correlated system of longitudinal and non-longitudinal profiles. In area prospecting of media which are nearly horizontally stratified, the longitudinal profiles represent a reference network, to which are related the non-longitudinal profiles. The number of reference profiles depends on the dimensions of the investigated area and on the detail to which the measurements are carried out. In reconnaissance area measurements of a definite section, it is usually possible to restrict oneself to two or three reference profiles with a loose network of longitudinal profiles which are placed at such distances from each other so as not to leave out unknown structures or other peculiarities of the geological structure.

In detail measurements, the profile network must be such as to insure the possibility of reliable correlation tracing of the waves, corresponding to the boundaries of interest to us, and a sufficiently detailed clarification of all the principal details of the investigated structures. The systems of non-longitudinal profiles are placed in this case in such a way as to insure closed correlation traverses of observations.

The interrelation of the observations obtained in individual profiles at a given type of measurement is carried out during the process of the measurement itself, by realizing where possible continuous correlation observation schemes.

In this type of measurement the same profiles are frequently covered simultaneously both as longitudinal and as transverse ones, in order to obtain a clearer picture in places where the correlation of the waves is violated.

In area prospecting of steeply descending layers or sharp angular discrepancies, and also of tectonic disturbances such as faults, which usually manifest themselves more clearly in observations on transverse profiles and on longitudinal ones, use is made of various systems of longitudinal and non-longitudinal profiles.

In the prospecting of steeply descending layers, which lie under a layer of loose rocks of small thickness (100 -- 200 meters), one determines the depth and relief of the surface of crystal rocks, places of vertical contacts, and also the boundary velocity in steeply-descending layers with the aid of longitudinal profiles, located across the extent of the layers. The tracing of lines of vertical

contacts is usually realized with the aid of transverse profiles, located also across the extent of the layers.

In investigation of faults (or, in general, of steps*) the fault line is usually mapped with the aid of transverse profiles, located across the extent of the fault (Fig. 34). The amplitude of the fault is determined with the aid of longitudinal profiles, located across the fault line and extending sufficiently far on the raised and dropped branches of the faults, where a complex wave pattern is no longer observed (Figs. 34, Long 1 and Long 2). In tracing these profiles it is necessary to bear in mind that at explosion points located over the raised branch, one obtains a clearer picture of the waves, characterizing the fault, then if the explosion points are located over the lowered branch. To refine the amplitude of the fault one uses also longitudinal profiles, located parallel to the fault line over the raised and lowered branches (Figs. 34 Long 3 and Long 4). The same profiles are used for correlation between the transverse profiles, which refine the position of the fault in plan. In shooting transverse profiles one uses explosion points located on longitudinal profiles, located above the raised and lowered branches of the fault.

3. Area measurements with the aid of a system of profiles using explosions in the single point. In the investigation of structures in those cases when the separation boundary is located at a considerable depth and the region of its tracing occupies a large area, it is advantageous to employ area measurements from a single explosion point. This type of measurement requires less labor compared with other systems of observations.

The explosion points, from which one shoots the system of profiles, should insure the possibility of carrying out large number of explosions; it is therefore best to place it in a natural body of water. In order for data of such an area measurement to obtain the fullest possible interpretation, this point of explosion must be placed on a longitudinal profile, from which it is possible to determine the absolute depths of the investigated boundaries and the values of the velocities.

Non-longitudinal profiles, which make up a net of profiles, are located dense enough so as to insure reliable

*In seismics, a step is taken to mean a radical shift in depth of the principal marking level. This shift may or may not be accompanied by a discontinuity in the layer, such as is characteristic of a fault.

correlation of the waves corresponding to the given boundary. When choosing the location of the network of non-longitudinal profiles in plan, it is necessary to take into account the effect of the seismic drift, which leads to a displacemnnt of the investigated portion of the boundary relative to the portion where the net of profiles is located, in the direction towards the point of explosion. This shift is the greater, the deeper the boundary. Fig. 35 shows a system of profiles used in measuring from a single point of explosion.

The mesurcement from a single point of explosion may be used not only to determine the relief of separation boundaries, which is done by using methods of quantitative interpretation of seismic hodographs, but also to separate the regions that are characterized by specific features of the shape of the recorded waves /18/.

Investigation of the zone of small velocities. The procedure of shooting a zone of small velocities does not differ in CMRW in anyway from the same procedure in the method of reflected waves /58/, and we shall therefore not treat this question separately.

A detailed calculation of the zone of small velocities in CMRW, as in the method of reflected waves, is necessary in those cases when a small-velocity zone changes substantially in thickness and velocity and when consequently it is impossible, in the interpretation of the hodographs of the refracted waves corresponding to the principal prospected levels, to confine oneself to introducing a certain constant correction for the zone.

6. Conditions of Excitation of Oscillations

To excite seismic waves one uses in CMRW explosions in wells, water reservoior, shot holes, excavations, on the surface, and in the air. In some cases (to solve miniature prospecting problems) shocks can also be used.

In the registration of the refracted waves, as in the registration of reflected waves, the principal requirements imposed on the excitation conditions are as follows: the oscillations should be sufficiently intense so that they can be registered at those distances form the point of explosion, which may be necessary in the specific prospecting conditions in the given region. Sometimes when prospecting at a depth on the order of 3 -- 5 kilometers and more, these distances reach 20 or 30 kilometers. In addition, it is necessary to cite in the explosion such oscillations, the frequency spectrum of which would be most

favorable for the registration with the aid of the seismic apparatus used for refracted waves both in the region of the first arrivals, as in the region of the subsequent ones. The pulse excited by the explosion should be sufficiently short so that one can separate on the seismogram the rapidly refracted waves. The excitation conditions should also be sufficiently stable, so as to insure good repeatability of the recording in observations along the entire profile or along a group of profiles, for example, in measuring from a single explosion point.

At the same time experience shows that the requirements imposed on conditions of excitation of oscillations in working with CMRW can be less stringent than in the reflected-wave method. The refracted waves can be always practically oscited (by making the explosions not only in shot holes, but also in wells, on the outside surface, etc.), whereas for excitation of reflected waves, even in the case of clear cut reflecting levels, it is usually necessary to have in addition favorable explosion conditions. This is connected principally with the fact that for reflected waves, which are usually traced in the region close to the explosion points, the surface waves may strongly interfere with certain other waves, which as a rule have less velocities and relatively rapid attenuation with distance; the intensity of noise of this type depends greatly on the explosion conditions.

For refracted waves, which are traced in the region more or less remote from the point of explosion, surface and other waves do not create noise, since they occur much later than refracted waves and in addition, at large distances, when they have a chance to attenuate. Another cause of the less stringent requirements on the explosion conditions when working with CMRW lies in the fact that the refracted waves usually have a lower frequency than the reflected ones, and it is easier to excite low frequencies with the explosion than high frequencies.

The principal factors that influence the intensity in the frequency spectrum in the recording of seismic vibrations are the conditions under which the explosive charge is placed. In explosions in shot holes, water reservoirs, excavations, wells, the intensity and frequency spectrum of the excited oscillations is determined essentially to be seismogeological properties of the rocks and the place of location of the charge. These properties include: velocity, density, plasticity, humidity of the rocks, presence of a level of ground waters, etc.

Experience shows that explotions in moist plastic

rocks (clay, marl, etc.) are more effective than explosions in dry loose rocks (sand, loess, etc.).

In addition, of great significance is also the depth of the displacement of the charge, and in the case of explosions in shot holes -- the water filling the hole.

In connection with the great variety of geological structures of surface layers in which the explosions are usually effected, it is difficult to give any specific indications on the degree of influence of any particular factor under various specific geological conditions. In practice therefore the most favorable explosion conditions are chosen experimentally.

The extensive experience in seismic prospecting work makes it possible to indicate several general premises concering shortcomings and advantages of various methods of excitation of oscillations.

Explosions in shot holes. The most favorable conditions of explosion in the sense of intensity and frequency spectrum of the excited oscillations, and also the repeatability of the form of recording, are explosions in shot holes filled with water, provided the charge is embedded in clay or other plastic rocks (marl, loam, etc.) below the level of the ground water. When working with CMRW one usually bores a hole 10 to 30 meters deep, so designed that their faces are in water-resisting rocks, which underly the level of the ground water.

Explosions in shot holes are used in CMRW most frequently, since in this case the system of profiles can be located in best correspondence with the problems of the prospecting, unlike when the explosions are carried out in natural water reservoirs and the profiles must be placed as functions of the locations of the water reservoirs. However, in explosions made in shot holes it is impossible to employ large charges repeatedly, more than 3 -- 5 kilograms, such as are necessary for large distances between the point of explosion and the instrument; after several such explosions the shot hole usually goes out of order, i.e., it either caves in, or explosions in such a hole, owing to damage to the walls, result in records that have low intensity, and low frequencies predominate in the frequency spectrum of the oscillations.

An example of the variation of the frequency spectrum of the recording due to damage to the walls of the well is shown in Fig. 36a and 36b. The seismogram in Fig. 36a was obtained by explosion in an undamaged hole, and the seismogram on 36b by explosion in a hole with walls that were damaged as a result of a large number of explosions. Both

seismograms were obtained for the same filtration of the apparatus. The comparison of the records from the accompanying seismograms shows that in explosions in an undamaged hole (Fig. 36a) one obtains a well-resolved record with the predominate frequency on the order of 60 -- 70, while in explosions within a damaged well (Fig. 36b) the recording is poorly resolved, and the predominating frequencies are almost half the value than in explosions with undamaged shot hole.

Experiment shows that charges up to 3 kilograms, under favorable explosion conditions in holes, insure the tracing of refracting holes at distances up to 10 -- 15 kilometers from the point of explosion. Usually these distances are sufficient for prospecting at a depth of 3 -- 5 kilometers, with the exception of regions with weak velocity differentiation of the rocks, where distances of 10 -- 15 kilometers can be found to be insufficient for such depths.

In passing through long profiles or in area measurements from a single explosion point, when it is necessary to make at one in the same point many explosions, one usually drills not one, but two or three and sometimes even more holes. When shooting longitudinal profiles the holes are located perpendicular to the profile line. When shooting transverse profiles located at a considerable distance from the point of explosion (1 -- 2 kilometers and more), the order of placement of the holes is immaterial, provided the distance between them does not exceed 3 -- 5 meters. In either case, when processing the data, the times of arrival of the waves are suitably corrected for the changeover from explosion in one hole to the explosion in another hole.

The number of necessary explosion holes depends to a considerable extent on the distances between the points of explosion and the seismographs, on the procedure of observation, on the conditions of placement of the charges, on the number of seismic-receiving channels in the seismic stations, etc. Usually in observations with standard 24-channel stations, with a spacing of 25 -- 50 meters between seismograms, the number of explosion holes required is approximately the same as in the method of reflected waves under the same conditions. At larger distances between the point of explosion, on the order of 5 -- 10 kilometers, the need for holes increases in the CMRW.

Explosion in water reservoirs. Good results are usually given such explosions in water reservoirs both closed (lakes, streams, etc.) as in open ones (rivers or seas).

Experience shows that the points explosions should be placed in water reservoirs in those places where the bottom is not covered with a thick layer of soot, since such a layer attenuates considerably the intensity of the oscillations and observes particularly high frequency, which leads to a reduction in the resolution of the method. The charges must be placed as deep as possible, for in this case the intensity of the excited oscillations is considerably greater than when the charge is placed at small depth.

A considerable advantage of explosions in water reservoirs is the possibility of obtaining records at long distances -- 40 or 50 kilometers -- when using relatively small charges (10 -- 50 kilogram of ammonite). In addition, at these points it is possible to carry out many explosions, for example several hundreds, still insuring good repeatability of the records.

The principal shortcoming of explosions in water reservoirs, as already indicated, is the fact that the choice of the system of observations is determined by the location of the reservoirs, and therefore as a rule the water points of the explosion are used as auxiliary ones, to supplement other methods of placing of charges, for example, explosion in bored holes (or wells, etc.), used in covering the principal network of profiles.

Substantial interference is produced when explosions in water reservoirs are used by repeated shocks, the appearance of which is due to the pulsations of the gas bubble in the water, this bubble being produced as a result of the explosion. These shocks, the number of which sometimes reaches 3, 4, or more, alternate in intervals of several hundredths or several tenths of a second, and are superimposed on the record so as to make the decoding of the seismograms very difficult. An example of a seismogram with a clearly pronounced repeated shock is shown in Fig. 37. The considerable intensity of the oscillations registered in repeated shocks, which exceed in some cases the intensity of the primary oscillations due to the explosion, is explained, as shown in reference /36/, by the fact that the frequency spectrum in repeated shocks is more favorable for excitation of refracted waves than the explosion spectrum.

The intensity of the repeated shocks can be attenuated or eliminated entirely by varying the magnitudes of the charges and their depths. Experience has shown, along with theoretical calculations, that repeated shocks have a weak intensity or vanish completely in explosions with a sufficiently large splash of water (i.e., as the charge

is increased or as the depth of burial is decreased).

Records of sufficiently satisfactory quality are produced also by explosions in excavations, which are cut down to the level of ground waters.

Explosions in wells and on the surface. In the case of explosions in wells and on the surface, low intensity and low frequency oscillations are excited as a rule. Usually, explosions of this type are used in the prospecting for shallow separation boundaries, when the refracted waves are traced on the seismographs essentially as primary waves.

Explosions in wells and on the surface, in view of the large consumption of explosive matter and the poor resolution of the seismic records, is recommended for use only in those cases, when for some reason there is no possibility of using other methods of exciting the oscillations, for example, explosions in bore holes and water reservoirs. It must always be borne in mind here that these explosions may not make it possible to obtain sufficiently resolved records and may thereby limit the prospecting capabilities of the method.

Explosions in air. The results of individual experiments of the application of aerial explosions in operating with the CMRW, to trace relatively shallow (up to one kilometer) refracting levels. In prospecting deep levels aerial explosions have not yet been used.

An important advantage of explosions in air is the fact that in this case there is no need for the expensive drilling of explosion holes. However, in this case, as a rule, it is impossible to obtain sufficiently intense records over considerable distances from the point of explosion (more than two or three kilometers), which restrict the application of this method of exciting oscillations.

The intensity of the record in aerial explosions may be considerably increased by using a grouping of charges, which in this case must be placed at a small distance, up to 3 -- 5 meters from each other. For a simultaneous explosion of charges it is necessary to employ in this case a detonating string.

Site of charge. In the CMRW, as in the method of reflected waves, an important role is played by the choice of size of the charge such as to insure high quality sufficiently intense records, by which it is possible to trace the ways of interest to us. The magnitude of the charges depend primarily on the conditions of excitation of the oscillations, on the distance from the explosion to the instrument, on the effective sensitivity of the apparatus, etc., and is determined experimentally. For example, in the

case of explosions in bored holes filled with water, drilled in clay-water-resisting rocks at a distance of 1.5 or two kilometers from the point of explosion, charges on the order of 0.2 -- 0.5 kilograms of ammonite are used; at larger distances from the explosion to the instrument (up to 10 -- 12 kilometers) one uses in some cases charges on the order of 1 -- 3 kilograms of ammonite.

Under particularly favorable conditions, the size of the charge at sufficiently large distances from the explosion to the instrument (up to 8 -- 10 kilometers), took place for example in Azerbaydzhan in 1944, and does not exceed 0.10 -- 0.15 kilograms of ammonite at holes 10 -- 15 meters deep.

In explosions in water reservoirs at the same distances, one usually employs somewhat greater charges (1 -- ½ or 2 times greater). However, in some cases, to the contrary, more intense records are obtained during explosions in water reservoirs, then during explosions in water holes. An example of this type is shown in Fig. 38, where the graph illustrates the character of the variation of the magnitude of the charge with the distance. This graph was plotted from data of observations, obtained with the station SS-24-48. As can be seen from the graph, the maximum charges at a distance of eight kilometers do not exceed two kilograms.

Explosions in wells, in dry excavations, and in air require a considerable consumption of explosive matter. The magnitude of the charge increases by a factor of two -- four compared with explosions in shot holes, and sometimes by a factor of several times ten.

It must be borne in mind that usually there is a certain relative limit for the magnitude of the charges used under different conditions of excitation of oscillation. As this limit is past, a further increase in the size of the charge, even a considerable one, no longer gives a noticeable increase in the intensity of the record. In such cases, to obtain a more intensive record it is necessary to resort either to essentially differing excitation conditions (for example, to increase the depth of the well, i.e., the depth of burial of the charge), or else it is necessary to increase the effective sensitivity of the apparatus (for example by using filtration, by using grouping, by improving the conditions of installation of the seismographs, by carrying out the observation during that time of the day, when there are no wind microseisms, etc.).

Shocks. In some cases in the study of the geological section up to depths on the order of 10 - 30 meters, for

example in the investigation of surface native rocks under "alluvia" in connection with searching for investigations under engineering structures, one can use shocks to excite seismic waves, (with the aid of a wooden hammer, etc.). Experience shows that in the case of shocks one observes for the most part well resolved oscillations, which can be traced at distances up to 150 -- 200 meters from the point of the impact. This method of excitation of oscillations makes it possible to produce multiply repeated impacts, of equal force, which is very important in studying the dynamic features of the waves. In this case the impacts are produced by throwing a heavy load weighing 50 - 100 kilograms from one in the same altitude.

In order to prevent the jars that are produced during the instant when the load is cast off, from being transmitted to the ground, the latter is suspended from a stationary mass to a mechanical filter, which represents a spring with additional load.

The instant of the impact is noted by recording it with the aid of special receiver, located in the base on which the load falls. The simplest method of noting the instant of the impact is used for this purpose of the record of the seismograph, located near the point of impact.

7. Conditions of Installation of the Seismograph

It has been shown experimentally that certain methods used in practice of installing seismographs are not satisfactory. These include primarily the mounting of the seismograph directly on the layer of the ground, rather than in wells filled with earth, mounting on the muddy layer, on solid crystalline and sedimentation-metamorphic rocks, and also all those cases when incomplete contact is produced between the bottom of the seismograph and the earth. In these cases, both in mounting on different rocks and in mounting on the same rocks, one usually observes the influence of the condition of the mounting of the seismographs on the character of the seismic records, manifesting itself primarily in the dependence of the predominant frequency and amplitude of the registered oscillations under the conditions of mounting of the seismographs, and secondly in the fact that the seismic records become complicated to a considerable degree by the presence of various kinds of interfering oscillations, principally the following: a) microseisms and b) natural oscillations in the resonant system, which is formed by the earth and the seismography mounted on its surface. The interfering oscillations, being super-

imposed on the record on the traced waves, cause phase shifts to be produced in the oscillations, and these phase shifts are not the same for the different channels. This deteriorates considerably the resolution of the record and makes it difficult to correlate the seismograms.

The effects of the conditions of seismography mounting on the seismic records play a considerably smaller role compared with the influences of the explosion conditions, but nevertheless their well becomes quite substantial in some cases, and one cannot neglect this factor. Therefore in carrying out work on CMRW it is necessary in all cases to strive for good contact between the bottom of the seismograph and the earth; the seismographs should as a rule be mounted in wells which are then filled with earth, and methods of the installation should be uniform over the entire profile. The seismographs must be mounted under identical conditions, avoiding installation of individual seismographs on roads, paths, mounds, ditches, wells, etc. It is best to mount seismographs on the side of such places, preferably in a direction perpendicular to the line of profile on longitudinal profiles it and along the profile in transverse profiles. To reduce the background of microseisms due to the wind, the seismographs must not be placed near bushes, single trees, etc., for near such places there is a very high level of wind microseisms (in very dense forests the level of microseisms is usually low). In order to eliminate sources of wind microseisms, the lead in wires of the seismographs should always lie on the ground, and not hang on the grass, etc. If these rules are observed, it is always possible to reduce considerably the microseism background, to average the conditions of installation of the seismographs along the profile, and to increase the effective sensitivity of the apparatus, which is particularly significant when working at large distances from the point of explosion.

To average the conditions of the installation of the seismographs and to reduce the background of microseisms, thereby increasing the effective sensitivity of the apparatus, it is also possible to employ grouping of seismographs. However, in this case the performance of field observations becomes very complicated, and in this connection the grouping is used only in those cases, when other simple measures do not insure the production of satisfactory records.

We consider below in detail the nature and the character of the interfering oscillations, due to resonance in the earth-seismograph system.

The form of the frequency characteristic of such an oscillating system depends on the magnitude of the total mass and radius of the base of the seismograph, and also on the magnitude of the velocity of the longitudinal waves and on the density in the small so-called contiguous layer of earth on which the seismograph is mounted /47/. Experience and theoretical calculations have shown that the resonant frequency of the system is the lowest for small values of the base radius and large weight of the seismograph. As the radius of the base is increased and as the weight of the seismograph is decreased, the frequency increases. Therefore, in order to shift the resonant frequency of the earth-seismograph system to the outside of the working band of the frequency, towards the higher frequencies, and thus eliminate the influence of the conditions of the installation on the seismograph records, the seismographs should be light and of relatively large radius of base.

If seismographs are mounted on loess rocks, characterized by small values of the longitudinal wave velocities and small values of the density, the resonance frequency is usually low; as the velocity and density increases, their frequency increases sharply.

Resonance manifests itself most sharply if the seismographs are mounted directly on the outside surface. Examples of resonance curves for the earth-seismograph system when the seismographs are mounted on surfaces of various sedimentation and crystalline rocks are shown in Fig. 39. As can be seen from the curves in this figure, in the case of mounting on dense clay, loam, and also on sand (curves 4, 5, 6) the resonant frequency lies in the range 150 -- 300 cycles, i.e., beyond the limits of the working range of the frequencies. When mounted on loose rocks, such as boggy peat soil, sand soil, and black-earth soils, or loess (curves 1, 2, 3) the resonant frequencies lie within the range of the working band (from 30 to 70 or 80 cycles), and this is undesirable, for in this case prolonged natural oscillations will be produced in the earth-seismograph system. Therefore the installation of seismograph on compact and dense ground is more favorable. If the seismograph is installed in a well which is subsequently filled with earth, the characteristics of the installation loose their resonant character in many cases.

Owing to the presence of the resonance phenomenon, the system earth-seismograph can be a source of long natural oscillations, which are produced in it under the influence of waves arriving at the seismograph.

These natural oscillations in the earth-seismograph system can in some cases cause considerable distortion of the seismic waves, introduce phase shifts which reach in some cases 0.02 -- 0.03 seconds, increase the duration of the individual groups of oscillations, etc. This raises difficulties in the correlation of the waves on the seismograms, leads to a deterioration of the resolution of the seismic records, and consequently to a reduction in the resolving ability of the seismic methods, i.e., to a reduction in the number of individual waves which can be separated on the records. The distortion of the shape of the oscillations of the waves makes it difficult to use in the interpretation such dynamic properties as the shape and amplitude of the waves. The influence of these natural processes is particularly dangerous in those cases when the resonant frequnncy of the earth-seismograph system is close to the predominant frequency of the registered waves.

Another very unfavorable case is when the resonant frequency of the system is close to the predominant frequency of the noise (surface waves, microseisms) which mask the reflected and refracted waves.

In addition, in connection with the fact that in practice the density and velocity in the earth change along the line of observation, the resonant frequency and the bandwidth of the earth-seismograph oscillating system also change as the seismographs are moved along this line. Consequently, unequal amplitude and phase distortions are introduced in the seismic records of different receiving channels, and this can also make it difficult to correlate the waves and to interpret the data obtained.

Consequently, resonant phenomena in the earth-seismograph system should be eliminated or at least attenuated. For this purpose it is necessary to shift the bandwidth of the system towards the region of frequencies that are higher than the frequency of the registered oscillations, and to increase the damping decrement in it. The shift of the band makes it possible to filter out the natural oscillations with the aid of the receiving apparatus. In practice, as is well known, this is realized by placing seismographs in shallow wells, approximately 20 -- 30 centimeters deep, which are subsequently filled with earth, and the earth as a rule is then tramped. Such a method of installing the seismograph reduces also the influence of microseisms due to wind on the seismic records.

Methods of mounting the seismographs. The tremendous variety in the soil surface, conditions in various regions of the USSR, and also the great differences in climatic

conditions, cause also a great variety in the methods of installing seismographs used in seismic prospecting.

The most favorable methods of installation in each new region are selected experimentally. At the present time there have been already developed in practice and extensively used the following methods of installation. On loose rocks and soils, the seismographs are palced in small wells 20 -- 30 centimeters deep which are subsequently filled with earth. It is usually not advisable to use wells deeper than 20 -- 30 centimeters for the installation of the seismographs, for this leads to an insignificant change in the characteristic of the system and in practice does not lead to an improved quality of recording. The principal effect on the characteristics is exerted by small, loosest layer of earth or rocks of thickness 5 -- 10 centimeters, lying directly under the bottom of the seismograph.

The form of the frequency characteristics of the installation depends to a considerable degree on the properties of the rocks, with which the well is filled. The use of sand to fill the wells when the seismographs are mounted on such soils as for example loose loams or rather analogous soils, increases the resonant frequency by 40 -- 50 percent, sometimes even more, compared with the value of the resonant frequency when the wells are filled with native rock. This also considerably increases the damping decrement of the system. By way of an example, illustrating the increase in the damping decrement of the earth-seismograph system and the attenuation of the natural oscillations in it when wells are filled with sand, Fig. 40 shows records of the natural oscillations (records of impact on a seismograph), obtained when a seismograph of type SP-7 is mounted on sandy earth in a well 20 centimeters deep without filling (Fig. 40 to the left) and with sand filling (Fig. 40, right).

In observations made on crystal rocks or dense sedimentation-metamorphic and sedimentation rocks, when the seismograms cannot be mounted in wells, it is best to mount the seismograms on a layer of sand several centimeters thick, specially placed for this purpose under the bottom of the seismograph. This makes it possible to mount the seismograph on rocks with the entire area of the bottom, and this first of all makes the installation identical along the entire profile, and secondly eliminates the possibility that the body of the seismograph would rock. In order to prevent the seismographs from the influence of the wind in this case, they should be covered with sand

or earth.

When working on boggy sections, a satisfactory method of mounting seismographs is to mount them in additional cases. The role of the additional case in this case reduces, on the one hand, to insulating a seismograph against moisture and preventing it against tilting in unstable ground, and on the other hand, to increasing the area of contact between the seismograph and the ground. In order for the seismograph to stand stably in the additional case, the latter is filled either with sand or with earth. Such a method of mounting it is possible also to rid of natural low frequency oscillations, which are excited in the earth-seismograph system. Good results in boggy sections is also obtained by installing the seismograph on wooden bases (pieces of wide board) and on wooden stakes, driven into the boggy earth at a depth of 1 -- 1.5 meters.

When working in winter conditions, the seismographs must be mounted directly on the frozen layer of ground, and in order to insure stable and reliable contact over the entire area of the seismograph bottom with the earth, they should be frozen to the earth.

In the presence of a snow covering, the seismographs can also be mounted directly on a packed layer of snow and covered from the top also with snow. This method of mounting seismographs, as shown by experience, is good as regards identity of installation conditions. In addition, this reduces slightly the background of microseisms by the wind.

8. Choice of Filtration for Work with CMRW

The working filtration of the apparatus is chosen experimentally. It depends on the seismogeological conditions of the region and on the conditions of the excitation of oscillations, which determine the frequency spectrum waves, and also on the required degree of detail of investigation of the seismic section.

Experience with CMRW work in different seismogeological conditions shows that in the investigation of small depths (on the order of 100 -- 200 meters) in the excitation of ocillations in bored holes, it is advantageous to use filtration, at which the maximum frequency characteristics of the apparatus are located at a frequency of 50 -- 70 cycles. For the station SS-24-48 this means filtration two or one, with the old choke (Fig. 8) and for the stations EKhO-1 -- filtration 1 -- 1 or 1 -- 3 (Fig. 5).

In regions where a strong background of wind in microsoisms is observed (usually these microseisms have a frequency on the order of 80 -- 100 cycles), and from which one cannot get rid by improving the conditions of seismograph installation, one chooses such a filtration, at which the maximum frequency characteristics would be at somewhat lower frequencies than the noise frequnncy.

We note that when using explosions in wells, even in investigation of small depths, it is impossible to work under the foregoing frequencies and it becomes necessary to resort to registration of lower frequencies, 25 -- 40 cycles. This leads to a reduction in the degree of details and accuracy of the prospecting.

In investigation of great depths, on the order of 1 -- 2 kilometers and above, when one usually employs considerable distances (5 -- 10 kilometers) from the point of explosion, the frequencies registered are usually 25 -- 40 cycles. In this case the reduction in the frequency is dictated essentially by the fact that the high frequencies are damped more strongly with distance, than the lower ones. Here use is made of filtration 2 or 1 with the new choke for the station SS-24-48 (Fig. 9) and filtration 4 -- 1 or 4 -- 2 for the station EKhO-1.

One working at still greater distances from the point of explosion, when it is necessary to increase substantially the effective sensitivity of the apparatus, it is recommended to change over to registration of low frequency oscillations, 15 -- 25 cycles. This is realized by going over to filtration 4 -- 4 on the station AKhO-1 (Fig. 7). The station SS-24-48 is not provided with this filtration.

If at greater distances from the point of explosion it is necessary to change from one filtration to another, then in the installation where the filtration is changed it is necessary to have records at both filtrations for identical explosion conditions. Otherwise the continuous phase correlation of the waves will become impossible or difficult.

9. Features of Techniques of Field Investigations in CMRW

The technique of carrying out field investigations in CMRW is essentially the same as in the method of reflected waves. Some slight differences in the technique of observations when working with CMRW are due to the fact that in this method one uses more complicated systems of observations (on longitudinal profiles) and greater explosion-instrument distances are used than in the method of

reflections. In addition, in the CMRW there is a greater use of explosions in water reservoirs. This leads to a certain complication in the technique of field operations, as follows:

1. In the CMRW on longitudinal profiles, the operations are carried out with simultaneous utilization of three, four, and sometimes more explosion points, which requires a more cumbersome organization of operations than in the reflection method. However, in this case the distance between explosion points is usually greater than in the method of reflections, and consequently the total number of explosion points on a profile of fixed length is as a rule less when working with the CMRW than when working with the reflection method.

2. In the investigation of large and medium depths one uses in the CMRW distances on the order of 10 -- 20 kilometers and more, which requires high effective sensitivity of the apparatus. For this purpose one resorts to registration at lower frequencies, one improves the installation conditions of the seismographs, one chooses quieter times of the day with respect to wind and other noise, and the conditions of strict quiet on the profile are observed, etc.

3. When working at high amplifier sensitivities the internal amplifier noise will increase considerably, and these produce in the seismograph frequent random oscillations, which, like microseisms, limit the further increase in the effective sensitivity of the receiving channel. Therefore whenever one observes on the seismograms a large noise background, it is always necessary first of all to verify the noise level in the amplifiers. The verification is carried out in the following manner: the seismograph is disconnected from the amplifier, as are the connecting leads; a resistance equivalent to the resistance of the seismograph and the connecting lead is connected to the circuit of the primary windings of the input transformer of the amplifier, operating at the employed gain; in this case the amplitude of the displacement of the light spot on the seismogram, due to only noise in the amplifiers, should not exceed one millimeter. If the noise level is above the permissible value, special measures must be taken to reduce the noise.

4. When working at large distances from the point of explosion, one uses also a greater spacing between seismographs. One seismograph stand may occupy an interval of more than two kilometers, and this increases the length of the connecting wires from the seismograph

to the station. If high sensitivity is used in this case, the ways of combatting various electrical induction (thunderstorm discharges, electric power lines, etc.) becomes a serious matter. One of the methods of eliminating noise of this kind is to shunt the primary winding of the input transformer by two series-connected capacitors 0.5 microfarad in each, with the center tap grounded. When operating at large distances from the explosion point, radio communication is essential.

5. In the CMRW, in order to make use of the dynamic properties for a quantitative interpretation, it is recommended to use calibrated step-line regulation of the sensitivity of the receiving channels. When such a regulation is used it is necessary, in addition to the ordinary verification of the apparatus for identity with respect to frequency and phase characteristics, also to monitor systematically the correctness of the calibration of the apparatus itself.

The technique of control and the technique of adjustment of seismic receiving apparatus in the CMRW are the same as in the method of reflected waves.

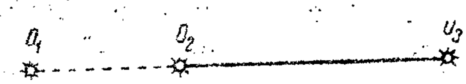


Fig. 16
Longitudinal profile. O_1, O_2, O_3 -- points of explosion.

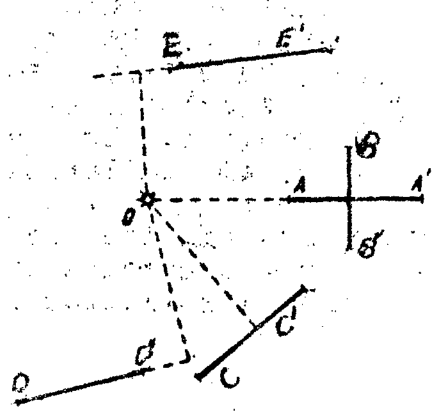


Fig. 17
Non-longitudinal profiles. BB' and CC' -- transverse profiles; DD' and EE' -- non-longitudinal (lateral) profiles; AA' -- longitudinal profiles.

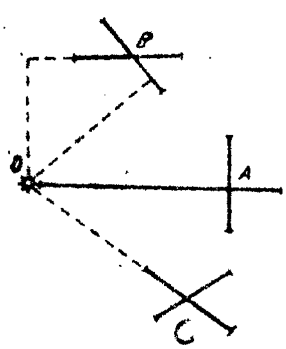


Fig. 18
Crosses of profiles: A--longitudinal and transverse, B--two non-longitudinal (lateral and transverse); C-- non-longitudinal (lateral) and longitudinal.

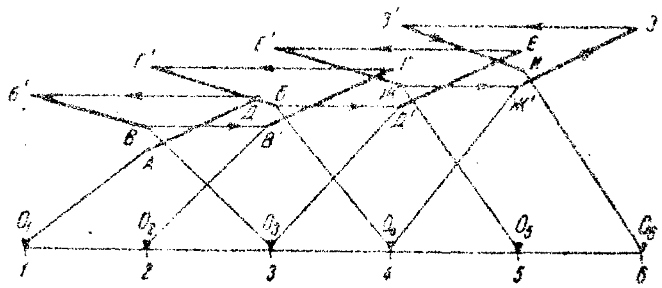
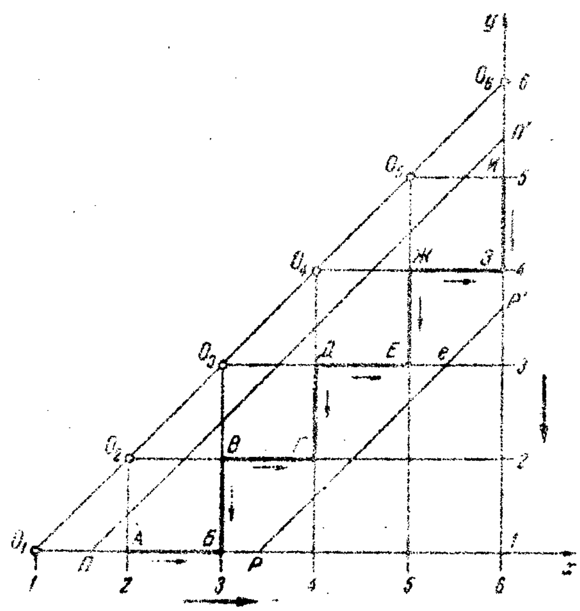


Fig. 19
Correlation system of opposing hodographs, insuring a continuous tracing of the phases of the waves along the profile.



/Fig. 20
Complete correlation system of observations, shown on the generalized plane. Vertical axis -- reverse path, horizontal axis -- direct path.

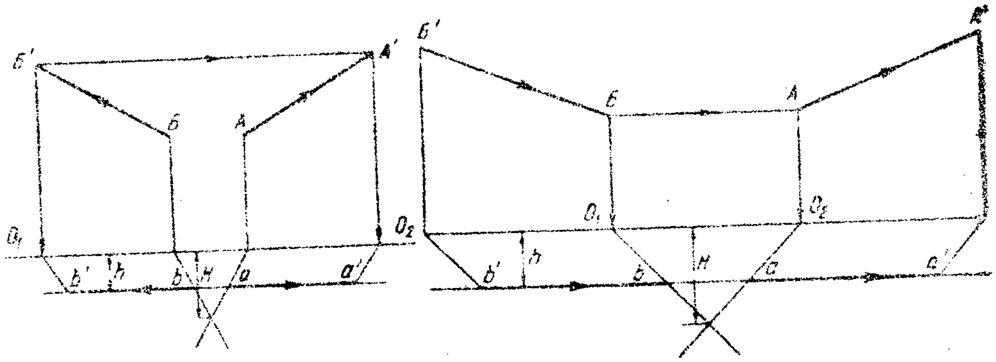


Fig. 21
Examples of correlation systems of observations, which do not insure the construction of a continuous refracting boundary. Along the section AA' of the boundary there are propagated waves, due to explosion at the point O_1; the corresponding hodograph is AA'; propagating along Section BB' are waves due to an explosion at the point A_2, and the corresponding hodograph is BB'. When $h > H$ these systems insure the construction of a continuous boundary.

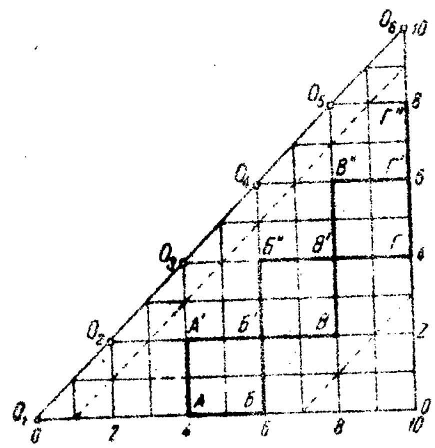


Fig. 22
Complete correlation system of observations, including the construction of summary opposite hodographs. AA'B'BA -- closed correlation path; --- boundaries of the region where the wave can be traced.

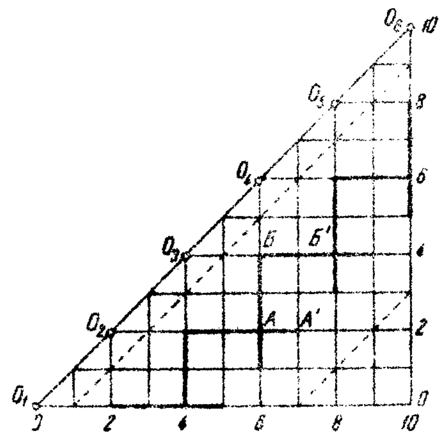


Fig. 23
Complete correlation system of observations, insuring the construction of summary opposite hodograph. System of open correlation paths.

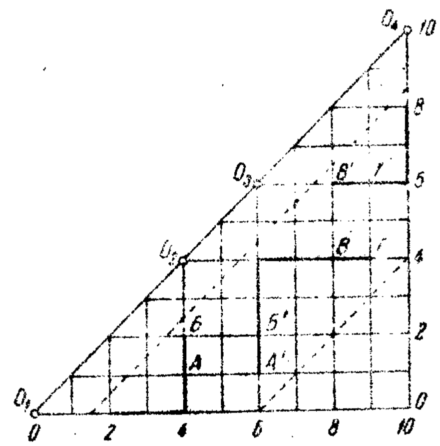


Fig. 24
Incomplete correlation system of observations, consisting of three isolated opposite traverses. The correlation interrelation is realized with the aid of overtaking traverse AB, A'B' and CD, D"D".

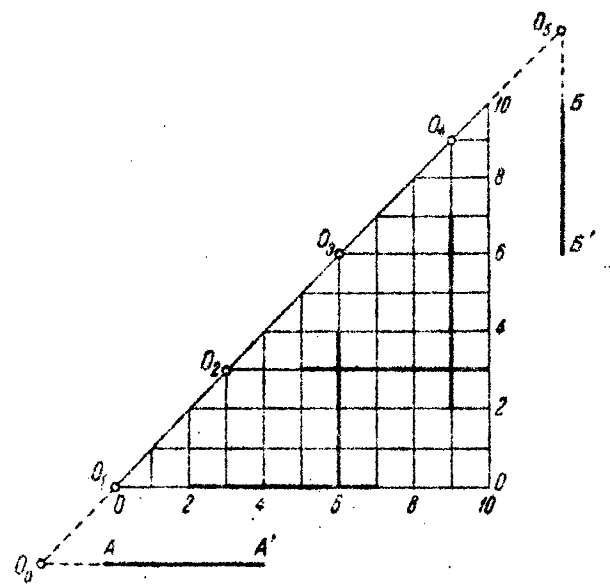


Fig. 25a
Supplement of the system of opposite traverses by means of overtaking traverses AA' and BB' from the bearing explosion points O_0 and O_5.

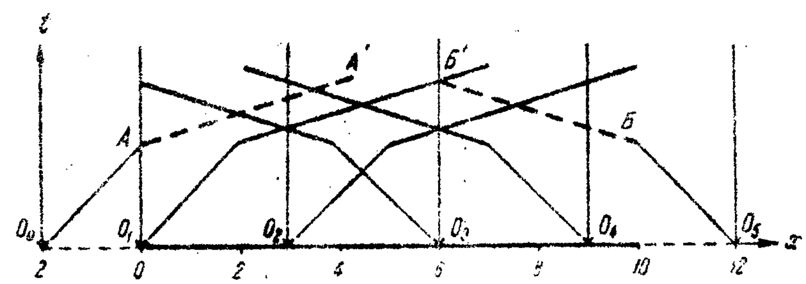


Fig. 25b
Scheme of hodographs for the system shown in Fig. 25a.

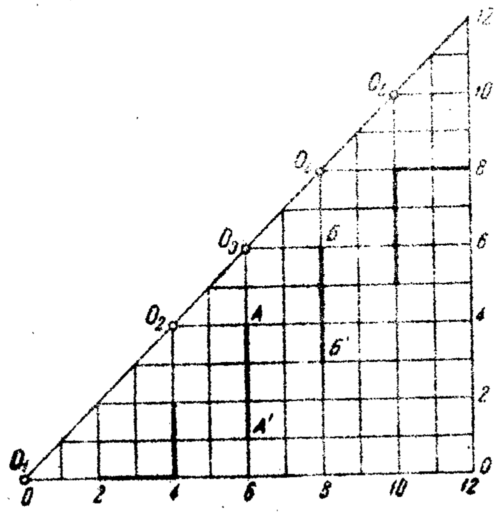


Fig. 26
Incomplete correlation system of observations. Two opposing isolated traverses are interrelated with the aid of two reverse overtaking traverses (AA' and BB').

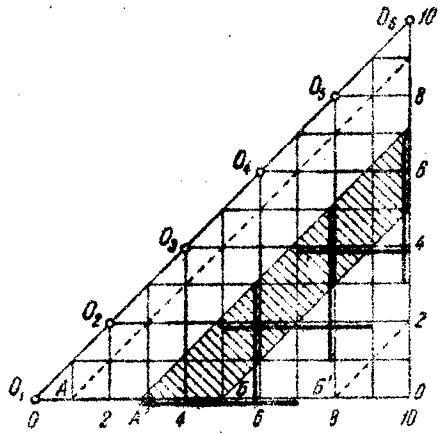


Fig. 27
Complete correlation system of observations in tracing two refracting separation boundaries. The shaded area denotes the region of joint tracing of two waves.

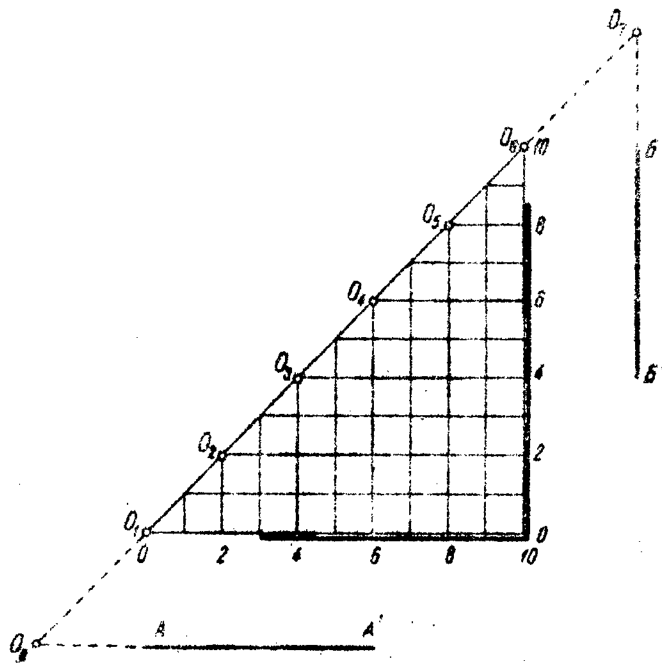


Fig. 28
Scheme of observation in the investigation of shallow and deep separation boundaries.

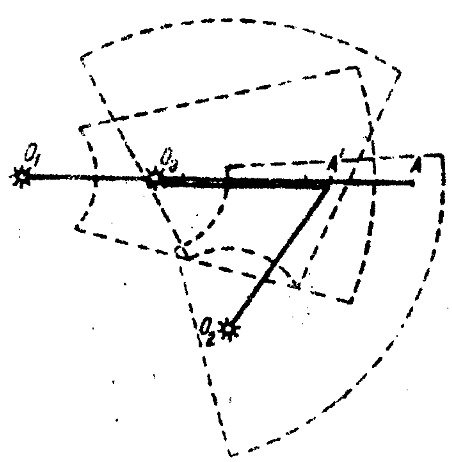


Fig. 29
Case of passage of section O_3A' of longitudinal profiles to serve as a transverse one. O_1 -- explosion point from which the longitudinal profile was shot; O_2 -- explosion point from which the interrelating profile O_2A' is shot. The dotted lines indicate the boundaries of the traceability of the waves.

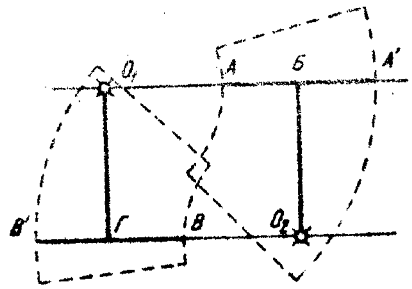


Fig. 30
Correlation interrelation of two longitudinal profiles (O_1A' and O_2C') with the aid of transverse profiles CO_2 and DO_1. The dotted lines denote the separation boundaries of the region of traceability of the waves.

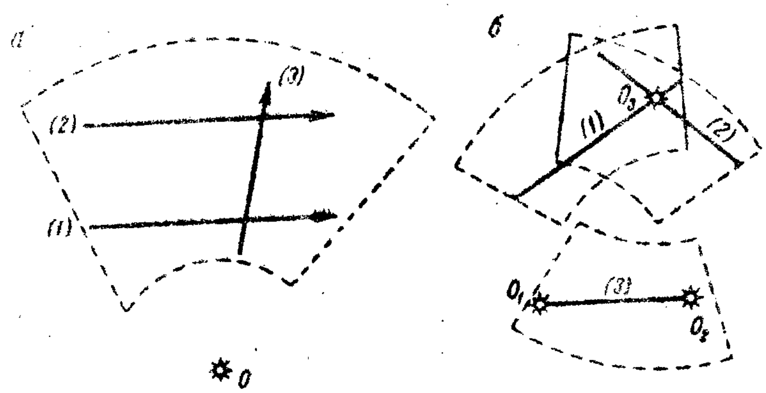


Fig. 31
A -- correlation between two transverse profiles (1) and (2), traced from a single point of explosion A with the aid of a longitudinal profile (3). B -- correlation of two isolated transverse profiles (1) and (2) with the aid of an auxiliary non-longitudinal profile (3), traced from the point of explosion O_3, located at the point of intersection of transverse profiles. The dotted lines indicate the separation boundaries of traceability of the waves, registered from different points of explosion.

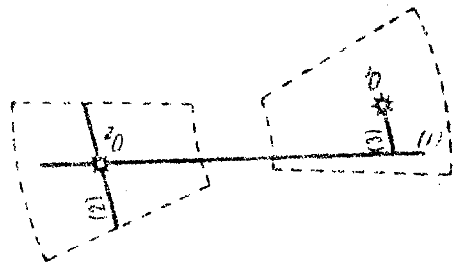


Fig. 32
Correlation between a longitudinal (1) and ~~non-longitudinal~~ (2) profiles with the aid of an auxiliary non-longitudinal profile (3) shot from the point of explosion O_2.

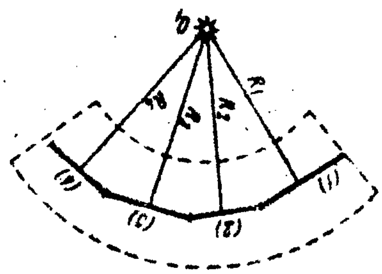


Fig. 33
Short transverse profiles (1), (2), (3), and (4), in the case of a separation boundary with inclinations greater than 10 - 15°.

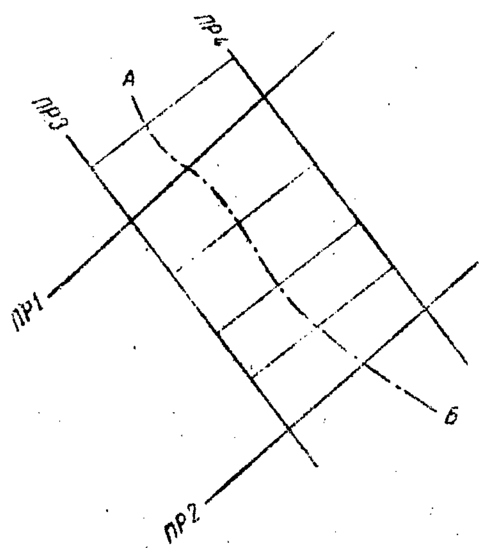


Fig. 34
System of longitudinal (numbers 1, 2, 3, and 4) and transverse (thin lines) profiles in the prospecting of a fault. AB -- fault line.

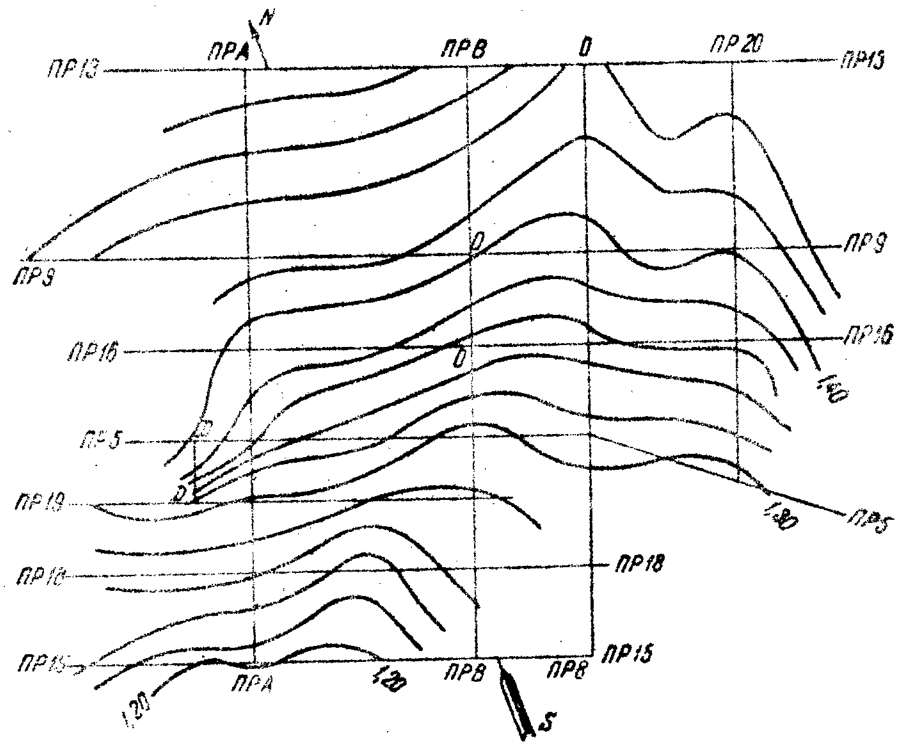


Fig. 35
System of longitudinal profiles in area measurement from one point of explosion. Straight lines -- seismic profiles, curves -- isochrons of refracted waves.

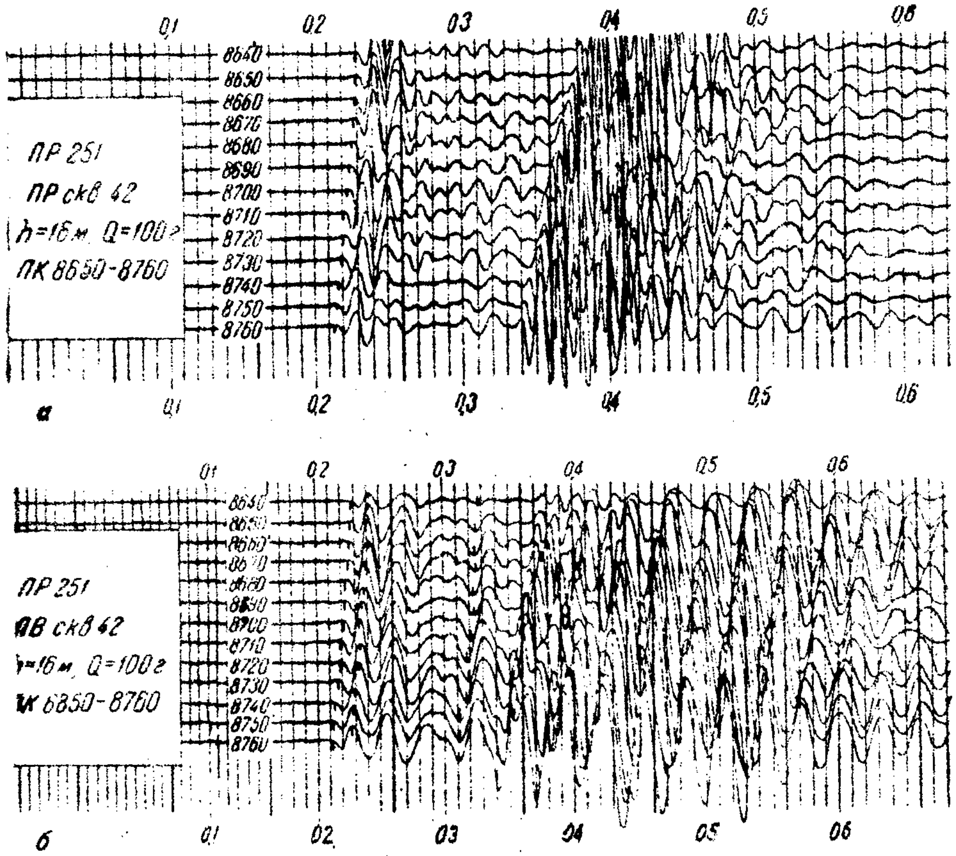


Fig. 36
A -- seismogram obtained by explosion in an undamaged hole;
B -- seismogram obtained by explosion in the same hole after several dozens of explosions have been made in it.

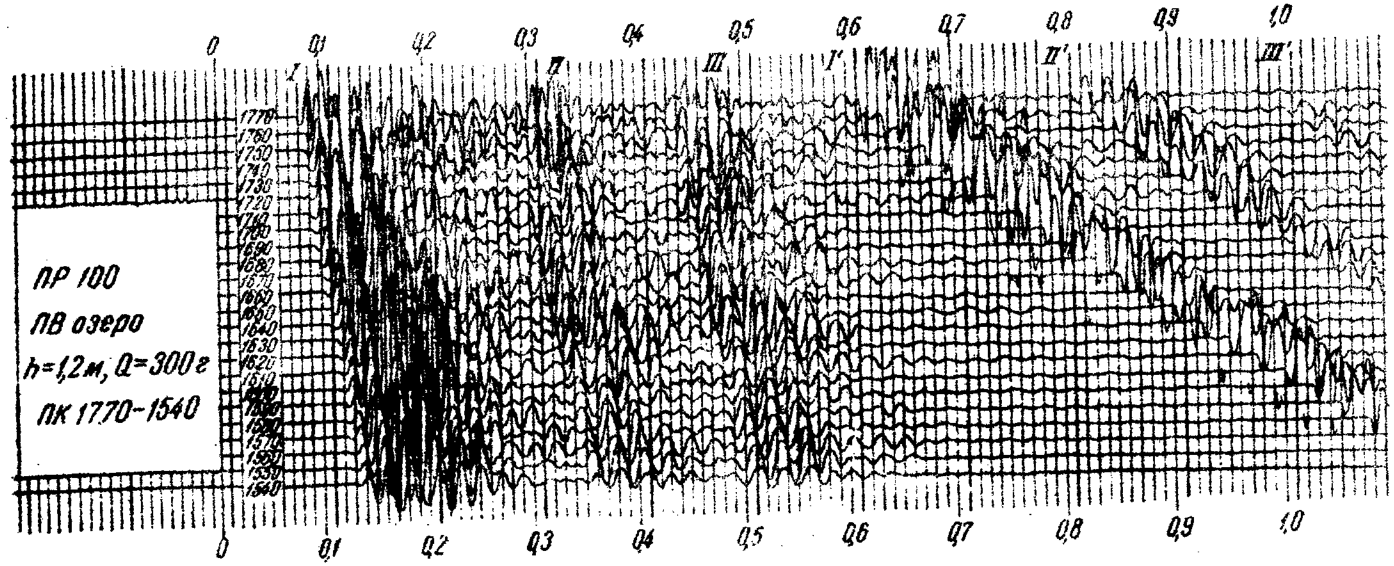


Fig. 37
Seismogram obtained in explosions in a water reservoir; it shows records of two repeated shocks. I and I' -- waves caused by the explosion; II and II' -- waves caused by the first repeated shock; III and III' -- waves caused by the second repeated shock.

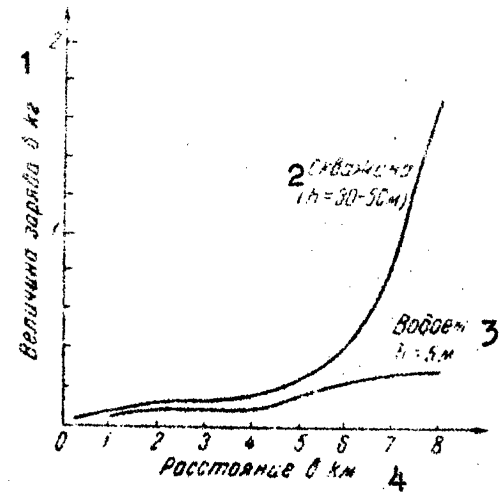
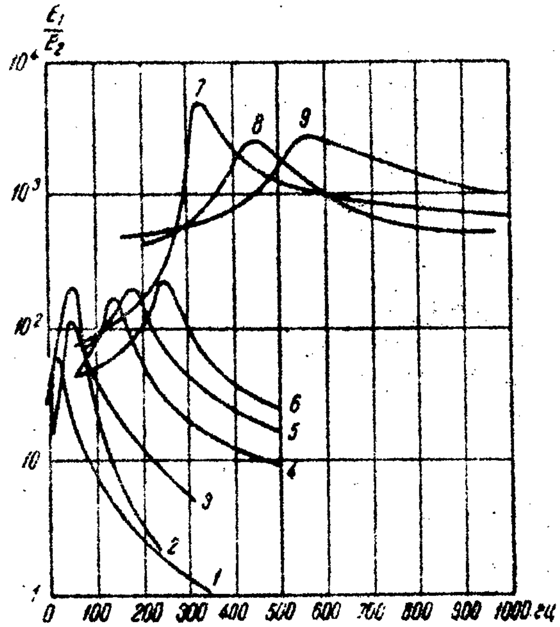


Fig. 38
Graph showing dependence of the magnitude of the charge and distance during explosions in water reservoirs and in a shot hole. 1) Size of charge, kilograms, 2) well shot hole (h -- 30 - 50 meters), 3) water reservoir, h -- 5 meters, 4) distance, kilometers.



Frequency characteristics of an installation consisting of two type SP-7 seismograph, rigidly screwed together, at different soils and rocks: 1 -- boggy peat soil; 2 -- sandy soil; 3 -- black-earth soil; 4 -- clay of Jurassic age; 5 -- clay of Jurassic age (seismograph mounted in a small well 40 cm deep; 6 -- quartz sand; 7 -- iron hornstone; 8 -- gneiss; 9 -- granite.

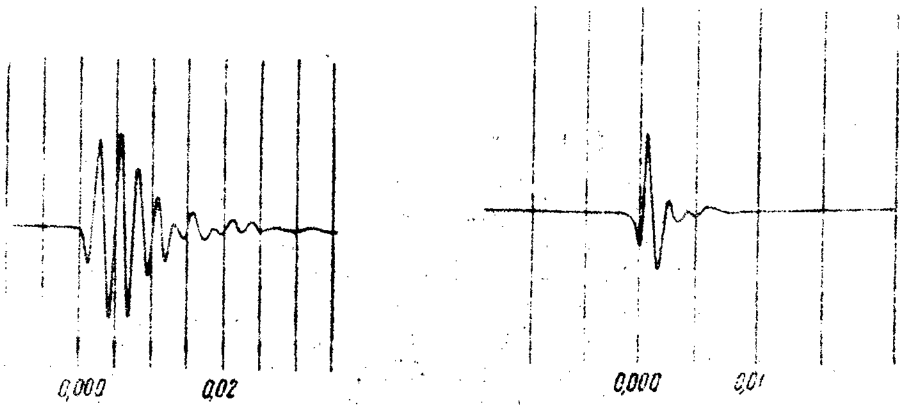


Fig. 40
Oscillograms that illustrate the influence of filling wells on the predominant frequency and the damping decrement of the natural oscillations in the earth-seismograph system. A type SP-7 seismograph was mounted on a sandy earth in a well 20 centimeters deep; left -- well not filled, right -- well filled with sand.

CHAPTER IV

CORRELATION OF REFRACTED WAVES

The correlation of refracted waves is the principal stage in the interpretation of the CMRW data, which determine the correctness of all the further constructions and inclusions concerning the structure of the medium.

The basic principles of correlation of refracted waves are detailed in references /16, 18, 24, 53/. Experimental data obtained in the Geophysical Institute Academy of Sciences USSR in the last few years have supplemented and broadened the concepts of correlation of refracted waves at different seismogeological construction of the medium. These data, along with the foregoing investigations, have been used in writing the present chapter.

1. Basic Criteria for Separation and Correlation of Refracted Waves

<u>Criteria for Separation of Simple Refracted Waves</u>. A simple refracted wave or merely refracted wave is called a wave corresponding to one refracting boundary. If two or several simple waves interfere with each other, they form an interference or complex wave. In the present section, we consider the correlation of simple waves.

It is necessary to separate on the seismograms and to trace waves that are characterized by stable form of record and an amplitude greater than the amplitude of the noise background, by a factor not less than three or four times. The basic criteria for the separation and correlation of a simple refracted wave are as follows:

1) Retention of the form of the record of the wave over the entire extent of the interval of tracing; the form or record is determined essentially by the predominating period, by the duration of the oscillations, and by the ratio of the amplitudes of the various phases of the wave.

2) Smooth variation of the amplitude of the wave with increasing distance from the point of explosion; usually the amplitude is decreased with increasing distance from the explosion point, but in some cases, for example, in the case of inclined separation boundaries, a certain increase in amplitude

with distance is possible.

3) The oscillations must be in phase.

The two first criteria are based on the use of dynamic characteristics of the waves -- the form and amplitude of the record; the third criteria is based on the use of kinematic characteristics of the waves -- the times of arrival and the apparent velocities that are based on these times of arrival. It must be emphasized that from the very beginning of the development of CMRW particularly great attention was paid to the use of dynamic features of records in the correlation of waves, whereas in the method of reflected waves, even in the modern stage of its development, the n-phase criterion is used predominantly in the correlation.

In the presence of waves with nearly equal apparent velocities, separated by small time intervals, which usually takes place in the method of reflected waves and is encountered relatively frequently in the CMRW, the correlation based only on the criterion of the in-phase nature of the oscillations leads to the fact that the waves corresponding to the different separation boundaries may be taken to be one and the same wave and continuously correlated on the recording. Such errors in the correlation may result in large errors in the plotting of the seismic sections and structural maps.

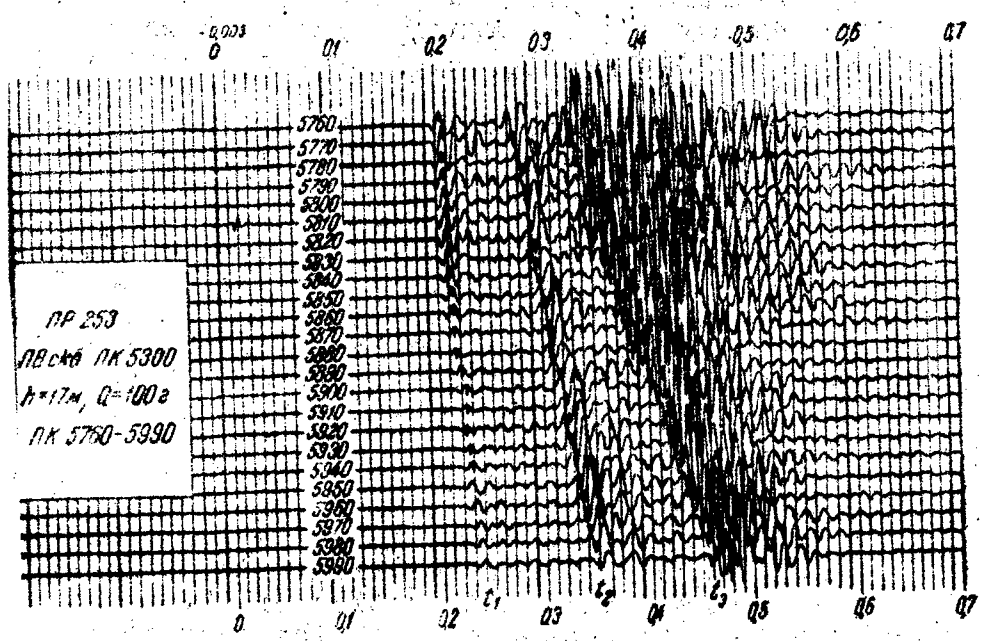


Fig. 41. Seismograms in which three refracted waves t_1, t_2 and t_3 are registered.

The dynamic features of refracted waves can usually be employed when they are separated and correlated, since the waves corresponding to different boundaries are frequently quite different in shape and recording intensity.

This facilitates the delineation of the regions of registration of different waves. An example of the seismograms on which are registered three refracted waves, separated by relatively small time intervals, is shown in Fig. 41.

Correlation of the Phases of the Wave. On seismograms, one usually correlates any extremum of the oscillation -- the maximum or minimum. In seismic prospecting, these extrema are usually called phases of the waves. The hodographs of the phases of the waves, as already noted in Chapter I, are usually parallel to the hodographs of the first arrivals of the waves.

For reliable tracing of the phases of the waves, it is necessary to obtain seismograms on which one sees clearly the entire form of the record of the wave. Seismograms with excessive intensity of recording, or the contrary, with too small an intensity of recording, and also seismograms with large noise background cannot be used in the correlation, since they cannot be used to trace the distinguishing features of the form of the recording of the different waves. In the correlation of waves based on records that are too strong or too weak, large errors are possible; in particular, waves corresponding to different refracting boundaries may be mistaken for the same wave.

In the correlation it is necessary to choose a phase of wave that differs by a noticeably large intensity from the preceeding phases and at the same time is sufficiently close to the start of the oscillation, since its phase is, for the most part, less distorted by interference with other waves than the phases that are later in arrival time.

Particularly significant is this factor in the correlation of first waves. In addition, in the correlation of phases that are closer to the start of oscillations, it is possible to determine more accurately the corrections for the time difference in the phases and for the first entry of the wave, which must be introduced in the quantitative interpretation of the observations (Chapter VI).

In some cases, the initial phases of the oscillations attenuate greatly as the distance from the explosion point is increased. This is observed principally in the case of thin layers /24/, and sometimes also for relatively thick layers which are located at low depths. This attenuation of the initial portion of the oscillations is connected with the fact that the high frequency components of the earth oscillations participating in the formation of the initial portion of the record of the wave are attenuated more strongly with distance than the low-frequency components. Fig. 42 shows an example of the record

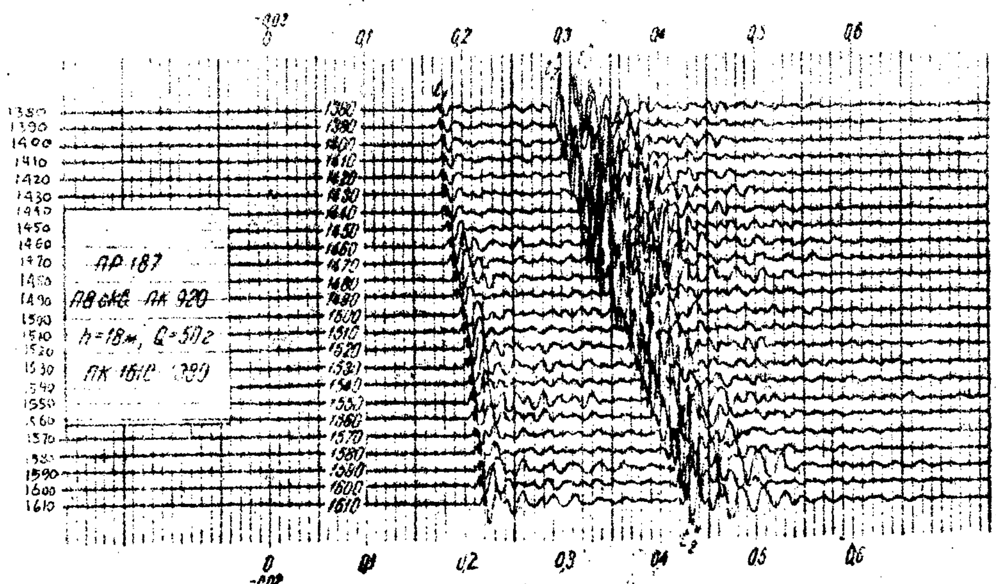


Fig. 42. Seismogram illustrating the attenuation of the initial phases of the wave with distance, t_2, t'_2, t''_2 -- different phases of the wave t_2.

on which sees the attenuation with distance of the initial phases of the wave t_2.

As the initial phases of the wave attenuate, it is necessary to proceed with correlation of the next phases, where it is necessary to trace both phases of the wave over the common interval of the profile, so as to have assurance that the hodographs of the different phases of the wave are parallel. Experience has shown that in the study of the separation boundaries located at depths from 50 to 500 meters, the hodographs of different phases of one and the same wave are always practically parallel: the exceptions are due principally to the superposition of other waves which may distort one of the phases of the wave.

In studying the separation boundaries that are located at small depths (less than 50 meters), one observes sometimes at short distances from the explosinn points that hodographs of different phases of one and the same wave are not parallel, owing to the increase in the predominant period of the wave with distance. This is due to the aforementioned faster damping of the high frequency components of the oscillations of the earth compared with the low frequency one.

Reproducibility of the Records of Refracted Waves. In order for the correlation of the phases of the refracted to be correct, it is very important that the recordings obtained at

one in the same stands at different explosions, as well as the recordings of the correlation instruments on going from stand to stand, be reproducible.

Experience of work with CMRW shows that, as a rule, the reproducibility of the records of refracted waves is good. An exception from this rule is encountered in two cases:

1) when the conditions of excitation of oscillations change, because of damage to the rocks during the explosion zone (in shot holes, wells, water reservoirs);

2) in the case of explosions in water reservoirs, when repeated impacts are produced due to the pulsation of the gas bubble /37/.

In the case of destruction of rocks within the explosion zone, the two following peculiarities of seismograms are observed:

1) there is a sharp increase in the predominant period of the wave, in which connection the difference is in the dynamic peculiarities of different waves becomes smoothed out and their resolution becomes considerably worse;

2) the ratio of the amplitude of the refracted waves to the amplitude of the microseisms is decreased, and the recording becomes less regular.

These two singularities of the seismograms are observed for the most part simultaneously. In this case, to improve the quality of the recordings and their reproducibility, it is necessary to change the point of explosion (Chapter III, Section 6).

In the case of repeated impacts in water reservoirs, the time interval Δt between waves due to the explosion and the pulsations of the gas bubble depends substantially on the magnitude of the charge and on its depth of immersion. Therefore, in the presence of repeated impact, the reproducibility of the recordings obtained at different explosions may be unsatisfactory. Waves produced by repeated impacts can be distinguished on the recordings from waves due to the explosion by the following symptoms;

a) the form of the recording in the inclination of the inphase axis of the waves due to the pulsations of the bubble duplicates the form of the recording and the inclination of the in-phase axis of the earlier arrival of the wave due to the explosion;

b) the time interval Δt between waves, due to the explo-

sion and pulsations, increases with increasing charge.

This cause for the violation of the reproducibility of the recordings can be readily eliminated since, by increasing the magnitude of the charge or by reducing the depth of burial (Chapter III, Section 6), it is possible to get rid of repeated impacts.

Length of the Interval of the Continuous Tracing of Refracted Waves. Depending on the seismogeological structure of the medium, the length of the interval of continuous tracing of refracted waves may vary. Refracted waves corresponding to boundaries of relatively thick layers, located at a great depth (H $>$ 300 meters) are frequently traced continuously over a large extent -- sometimes up to ten kilometers and more. Refracted waves corresponding to boundaries of thinner layers, no matter what their depth, are frequently traced only over comparatively short intervals -- on the order of several hundreds of meters. Refracted waves corresponding to boundaries of both thin and relatively thick layers located at shallow depths (H $<$ 100 meters) are frequently traced only over several tens of meters, owing to the strong damping of the waves with distance.

The length of the interval of continuous tracing of refracted waves corresponding to different separation boundaries is frequently reduced considerably because of interference of the traced waves with other waves.

Correlation Interrelation of Waves. The principal method of correlation interrelation of the waves registered at different explosion points is interrelation by mutual points. The correlation of waves that are registered at mutual points of the profile is usually realized quite reliably by the kinematic feature -- the times of arrival of the waves. Correlation of waves at mutual points by dynamic features of the recordings can also be carried out in the most cases reliably, but sometimes one observes differences in the form of the recording of the waves, due principally to differences in the conditions of excitation of the oscillations in both points of explosion. In particular, such cases are encountered if the explosions in one of the points are done in dense rocks (for example, in limestones or dense clays), and in the other points, in loose ones (for example, loams or loess).

Correlation interrelation of waves on the basis of overtaking systems is based primarily on the criterion of the fact that the overtaking hodographs are parallel.

The dynamic features of the recordings, in particular the ratio of the amplitudes of the considered waves and other waves, cannot always be used for the identification of the waves, registered on the overtaking systems. This is connected with the fact that the different waves are damped differently with distance, and therefore the ratio of the ampli-

tudes of the waves on the recordings, obtained at the close and far point of explosion may be substantially different (Section 6).

In some cases, for example in the study of vertically stratified media, the correlation interrelation of the waves by means of overtaking systems is of primary significance (Section 7), but in most cases it is a supplement to the principal method of interrelation by mutual points.

Interchange of Refracted Waves. In the correlation of refracted waves it is very important to exhibit the appearance of regions, in which the wave corresponding to one refracting boundary, or by a complicated oscillation which is a result of interference of two or several waves, corresponding to different separation boundaries. In the following discussion, the term interchange of refracted waves will mean the two following cases:

1) when a simple wave, corresponding to a single refracting boundary, is replaced by a simple wave, corresponding to another boundary;

2) when a simple wave, corresponding to a certain refracting boundary, is replaced by an interference of complex wave.

The latter case is encountered particularly frequently in seismic prospecting practice. Thus, the term "interchange of waves" is understood in the broader sense of the word. We shall henceforth consider the question of how to recognize interchanges pertaining to the above two cases.

Criteria for Recognizing Interchange of Waves. The principal criteria for the establishment of interchange of waves are the following:

1) the presence of two simple waves with intersecting or strongly approaching in-phase axis on one and the same profile interval;

2) change in the form of the recording;

3) radical change in the amplitude of the wave;

4) change in the degree of damping of the wave with distance;

5) change in the apparent velocities.

In practice, in the interchange of waves one frequently encounters combinations of several or sometimes all of the foregoing symptoms (Fig. 43).

Interchanges of this kind can be most readily observed

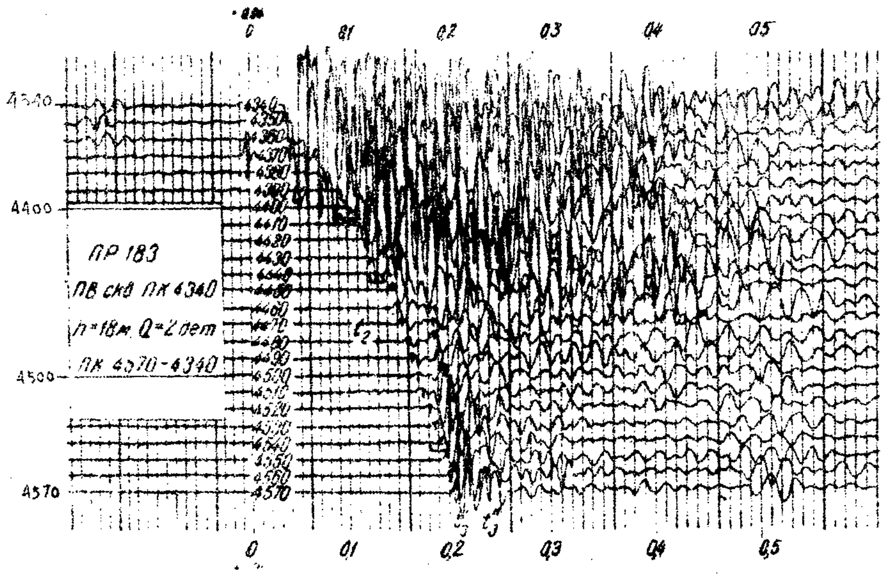


Fig. 43. Seismogram on which one notes interchanges of refracted waves t_1, t_2 and t_3. The symbol ⌐¬ denotes an interchange of the waves.

in the correlation of seismograms.

However, sometimes one observes only certain or only one of the foregoing symptoms of wave interchange. This makes some cases the disclosure of the interchange quite difficult, since one of the symptoms, particularly the change in the apparent velocity, is insufficient for a unique solution of the problem of the presence of wave interchange. Let us stop to examine each of the foregoing symptoms separately.

The presence on the seismograms of two simple waves with intersecting or greatly approaching in-phase axis is the strongest symptom of wave interchange. Two cases of wave interchange are possible here:

a) both simple waves begin to interfere with each other over a certain interval of the profile, and the simple wave is replaced by interference wave (Fig. 44);

b) one of the waves can no longer be traced to the start of the zone of interference, and then one simple wave is replaced by another simple wave (Fig. 45).

In other cases, the region of simultaneous registration of two interchanging simple waves is absent, and consequently the first criterion for establishment of the interchange of waves is lacking (Fig. 46).

From among the remaining four symptoms of wave inter-

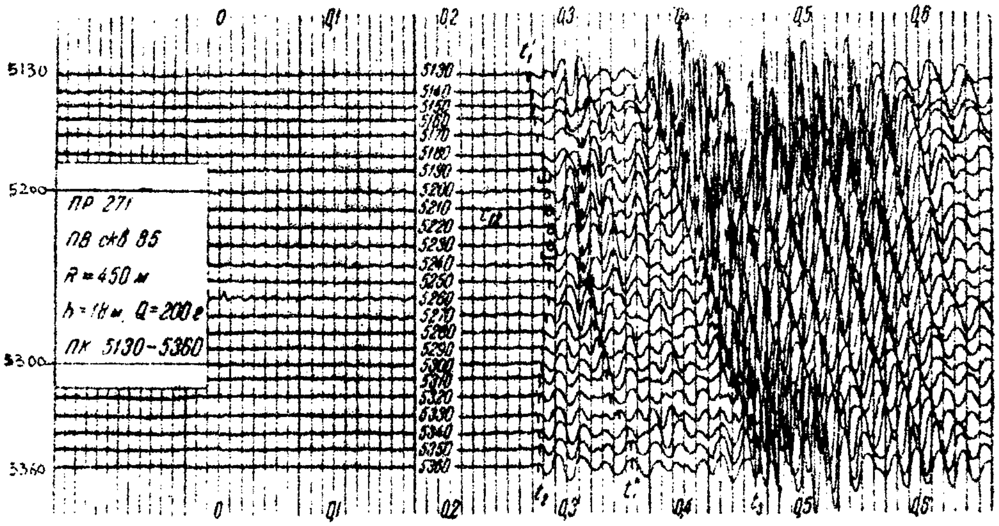


Fig. 44. Seismogram on which is noted the interchange of a simple wave by an interference wave. t_1 and t_2 -- simple waves; t_{12} -- interference wave.

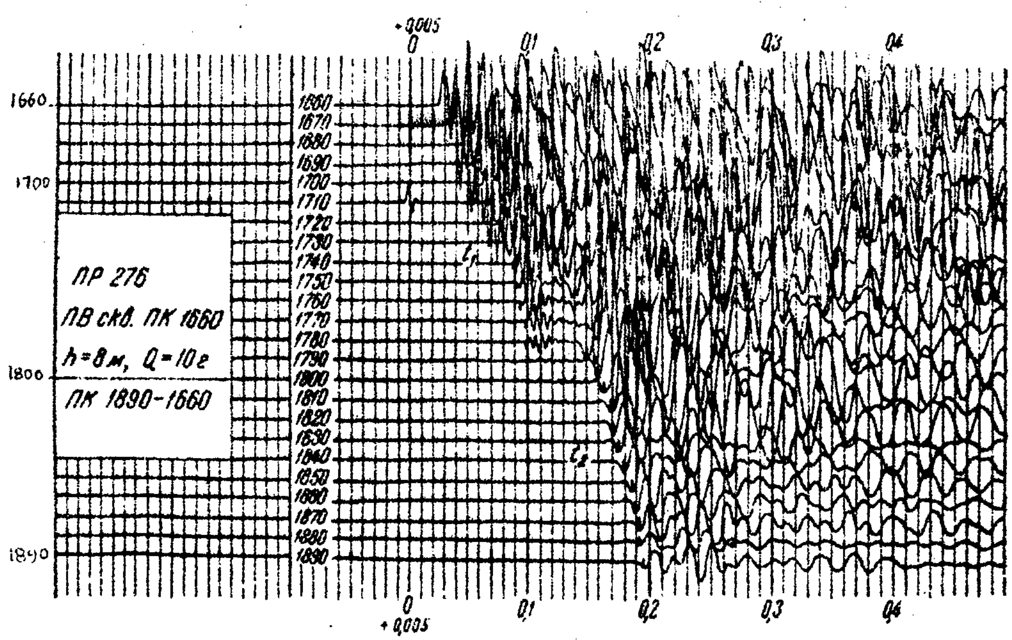


Fig. 45. Seismogram on which the wave t_1 is damped prior to the start of the zone of interference with wave t_2.

change, the strongest is the change in the shape of the recording (Fig. 47); the change in the predominating period of the oscillations or its duration or the ratio of the amplitudes of various phases is a reliable criterion for the exhibition of the interchange of waves even in those cases when the remaining symptoms of the interchange are lacking.

In many cases even weak changes in the form of the recording, particularly certain complications of the form of wave recording -- appearance of points of inflections, additional extrema on the background of the main oscillation, etc., -- are evidence that the traced wave has been replaced by another simple wave or by an interference wave.

A sharp change in the amplitude of the wave is a less pronounced indicator of a change in the wave picture than a change in the form of the recording, since in some cases the changes in the amplitude connected with interchange of simple waves or with their interference are masked by a continuous decrease in the amplitude of the wave with increasing distance from the explosion point.

However, in some cases, particularly in the investigation of vertically stratified media, a sharp increase (Fig. 46) or reduction in amplitude is observed with increasing distance from the explosion point, confirmed by observations at several explosion points. Such changes in the amplitude are frequently reliable symptoms of wave interchange. In most cases, it is possible to determine from the changes in the amplitude quite reliably the start of the zone of wave interference (Fig. 43).

The change in the degree of attenuation of wave with distance is a weaker symptom of interchange of waves and the two preceeding ones. In some cases the change in the degree of damping of waves with distance may be connected not with an interchange of waves, but with a change in the thickness of the layer.

From the experimental data, it is known that the refracted waves corresponding to thin and protruding layers, particularly strongly damped with distance (Sections 4 and 9 /24, 10, 35/).

Sometimes, the change of degree of damping of the waves with distance may be connected with changes in the form of the refracting boundary. Therefore, in the absence of other symptoms of wave interchange, to determine whether there is an interchange, it is necessary to compare records obtained at several explosion points; sometimes, this question can be resolved only after plotting graphs of the variation of the amplitude with distance and determining the boundary velocities.

The change in the apparent velocity is the weakest of all the foregoing symptoms of wave interchange and, like the symptom of change in the degree of damping of the wave with distance, it can be due to other causes and particularly to the

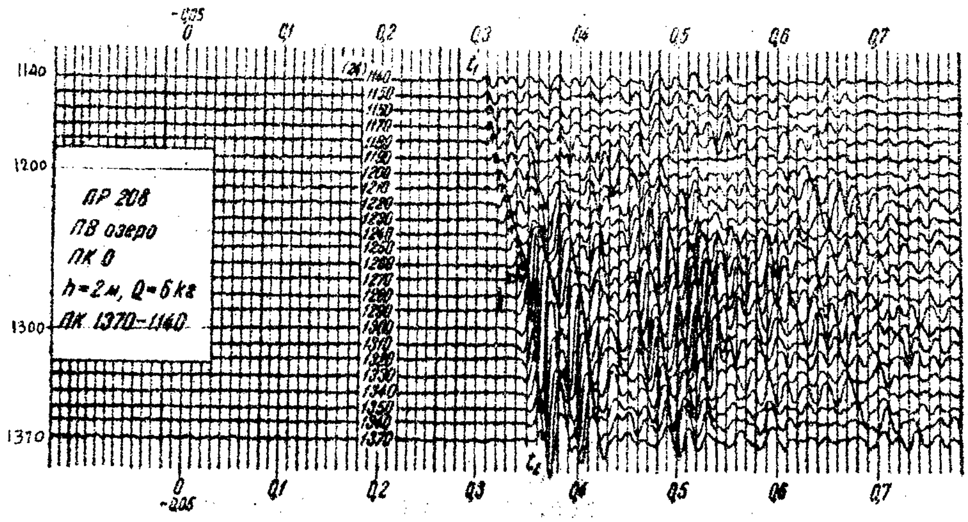


Fig. 46. Seismograms on which the interchange of wave t_1 by wave t_2 is noted from the change in the form and from the sharp increase in the amplitude of the recording. The arrow ↑ indicates the direction of increasing amplitude of the recording.

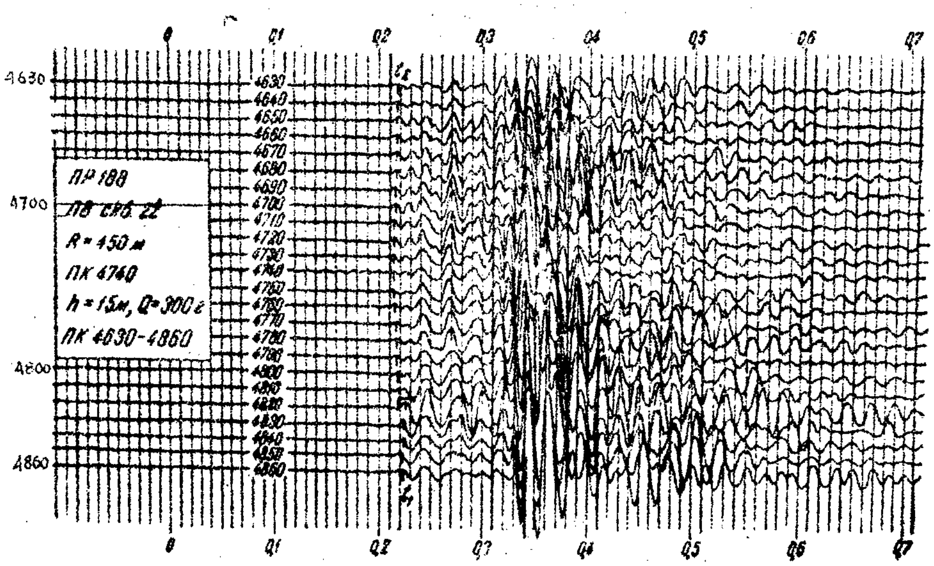


Fig. 47. Seismograms on which the interchange of waves t_1 and t_2 is noted from the change in the form of the recording.

change in the relief of the refracting boundary. Therefore, in the absence of other symptoms, it is necessary to compare carefully the changes in the apparent velocities obtained at different explosion points in order to establish whether this change in the apparent velocity is due to wave interchange or to a change in the relief of the refracting boundary.

It must be noted that in some cases one or several of the foregoing symptoms of wave interchange may be due to a local change in the properties of small-velocity zone.

In such cases, the foregoing dynamic and kinematic singularities of the recordings are observed only over a short interval of the profile, and unlike the case of wave interchange, the character of recording on both sides of the zone where the correlation is violated is usually almost the same. In the presence of several points of explosian and for longitudinal profiling, or in the case of area measurements with a single common explosion point, such local zones of violation of correlation can be readily distinguished from wave interchange.

It is particularly simple to observe the foregoing local changes in properties of the surface layer in those cases, when several waves are registered, corresponding to different separation boundaries. In this case, the changes in the form of the recording, in the amplitudes, and in the apparent velocities are observed simultaneously on all waves. At such local changes in the form or amplitude of the recording, one must not note a wave interchange in the correlation, but it is necessary to mark with a special symbol the discontinuity in the correlation of one and the same wave.

On the Detection of Wave Interchange in Different Methods of Regulation of the Sensitivity of the Apparatus.

For any method of regulation of the sensitivity of the seismic receiving apparatus, a change in the form of the recording and a change in apparent velocities is directly evident from an examination of the seismograms.

To identify amplitude symptoms of wave interchange -- changes in the amplitude of the wave and in the degree of its damping with distance -- it is necessary to control the sensitivity of the apparatus. In production seismic operation, both by the reflected wave method and by the correlation method of refracted waves, the control over the sensitivity of the apparatus is usually lacking. The regulation of the sensitivity of the channels is realized in such a way that, on the recordings of all the channels, the amplitude is approximately the same. For this purpose, the sensitivity of the channels to which the seismographs furthest away from the point of explosion are connected is increased, compared with the sensitivity of the channels which are connected to seismographs which are closer to the point of explosion. With

such a method of control of sensitivity of the channels and in the absence of sensitivity control, the detection of amplitude singularities in the waves and the observation of wave interchanges at which there are no noticeable changes in the form of the recording and the magnitude of the apparent velocities is in many cases practically impossible.

The cmtrol over the sensitivity of the apparatus which is necessary for the exhibition of amplitude singularities of the waves can be realized by various means (Chapter II, Section 3). Experience of working with the correlation method of refracted waves carried out by the Geophysical Institute has shown that the method of controlling sensitivity ofthe channels which is most convenient for the detection of amplitude singularities in the waves is a method by which all che channels have equal sensitivity /9/.

In this case, the amplitude of one in the same wave is different on recordings made by different channels. Figs. 41 and 46 show seismograms obtained at equal sensitivity of the channels. There is no wave interchange on the seismogram of Fig. 41, and the amplitude of the wave decreases smoothly with increasing distance from the point of explosion. On the seismogram of Fig. 46, one sees clearly a wave interchange characterized by a sharp increase in the intensity of the recording at a certain distance from the point of explosion.

In some cases it is difficult to employ in practice the method of equal channel sensitivity. This is particularly difficult to use at large distances between seismographs. In these cases, the amplitudes of the waves on the channels corresponding to the seismographs that are closest to the point of explosion, are too large and in the channels corresponding to the seismographs that are farthest from the point of explosion they are too small.

This makes it difficult to correlate the waves correctly. The same difficulties may arise also at small distances between seismographs and in the case of strong damping of waves with distance. In such cases, it becomes necessary to adjust the channels for different sensitivities and to record, in addition to the seismogram, also the control of the sensitivity of the apparatus. If the sensitivity of the channels is calibrated, the allowance for the differences in sensitivity of the apparatus becomes greatly simplified.

It must be noted that at different channel sensitivities, even in the presence of sensitivity control, the detection of wave interchanges by amplitude symptoms is somewhat more complicated and requires consumption of more time for correlation than in the case of equal channel sensitivity.

<u>Detection of Replacement of a Simple Wave by an Interference Wave</u>. It is necessary to distinguish three possible cases of interchange between a simple and interference oscillations, shown schematically in Fig. 48.

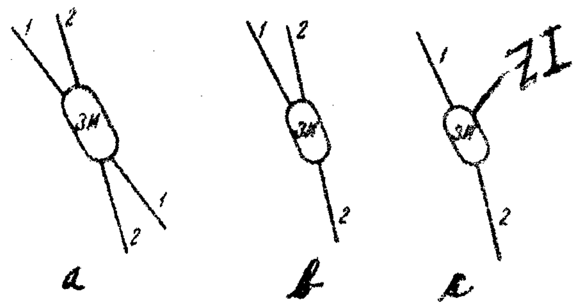


Fig. 48. Diagram showing three cases of interchange of two simple waves by an interference wave. 1, 2 -- in-phase axis of simple waves t_1 and t_2; ZI -- interference zone of waves t_1 and t_2.

1. Intervals exist ahead and past the interference zone where both waves t_1 and t_2 are traced, and they are separated by a sufficient interval of time (Fig. 48a and Fig. 49). This case is encountered quite frequently in the investigation of media that are close to being horizontally stratified and regions where both waves are registered on the same intervals of the profile and are separated by a considerable time interval may in some case be quite extensive. This case is encountered sometimes also in the investigation of media which are close to being vertically stratified, and in these cases the region of simultaneous registration of waves outside the zone of their interference and the zone of interference itself are as a rule small in extent (Section 7).

2. The region where the waves t_1 and t_2 may be traced separately on the same recordings located only on one side of the interference (Fig. 48b and Fig. 50). This case is frequently encountered in the investigation of horizontally stratified media, particularly in those cases when one of the interfering waves (for example t_1) is relatively rapidly damped with distance and therefore cannot be separated on the recordings past the zone of its interference with the other wave t_2.

3. There is no region where the waves t_1 and t_2 may be traced separately on one and the same recording, i.e., one wave t_1 is traced on the profile lines followed by the result of summation of two waves, and then again by one wave t_2 (Fig. 48 and Fig. 51).

This case is encountered in practice in the investigation of media which are close to horizontally stratified, principally at weak differences in the velocities in individual layers. In these cases, the zone of interference of two waves can be quite extensive. In the investigation of media which are close to vertically stratified, this case is frequently encountered, and the extent of the interference zone

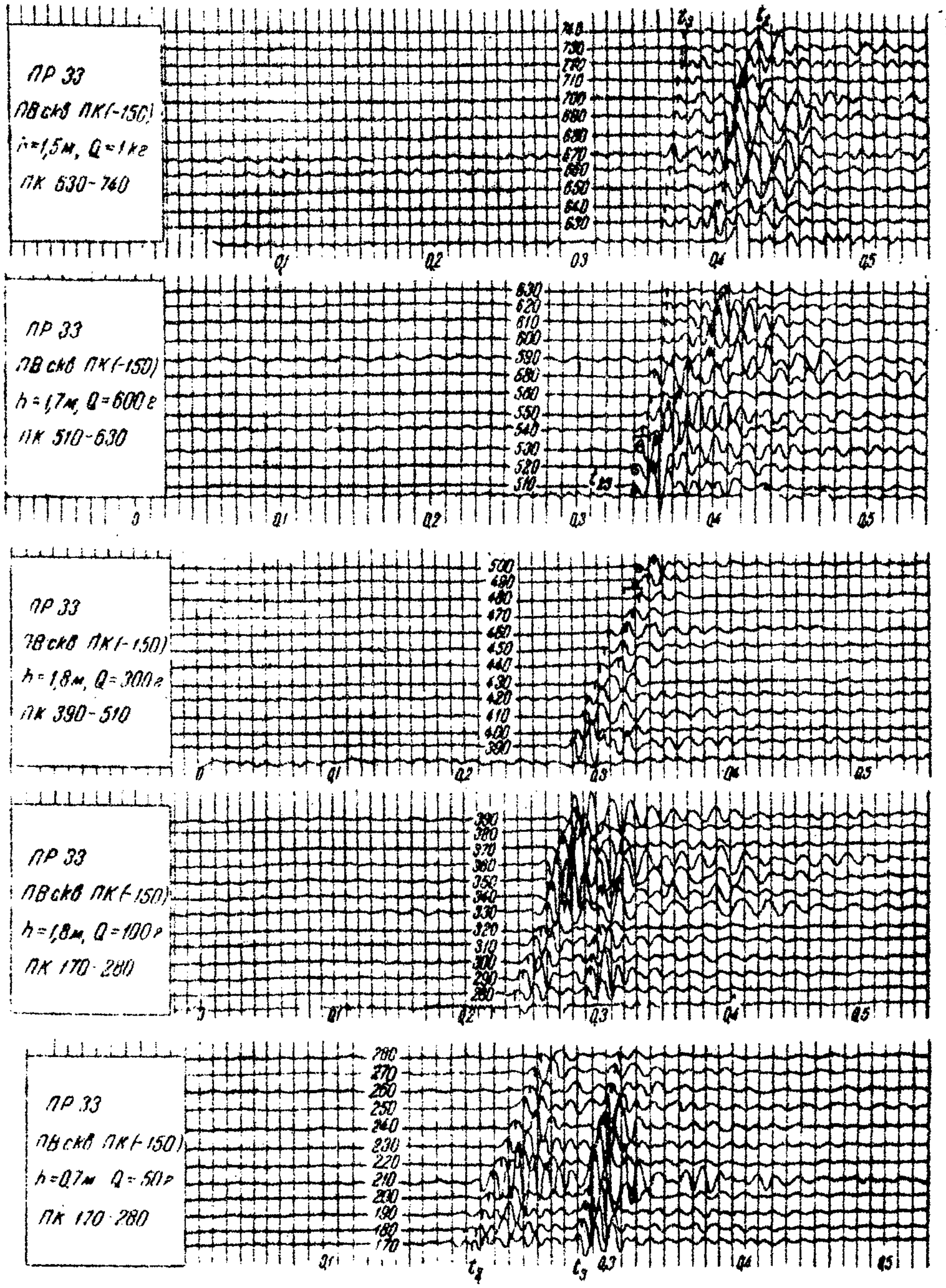


Fig. 49. Seismograms which illustrate the interference of two waves t_2 and t_3 traced on the same intervals of the profile on both sides of the interference zone.
t_{23} -- interference wave.

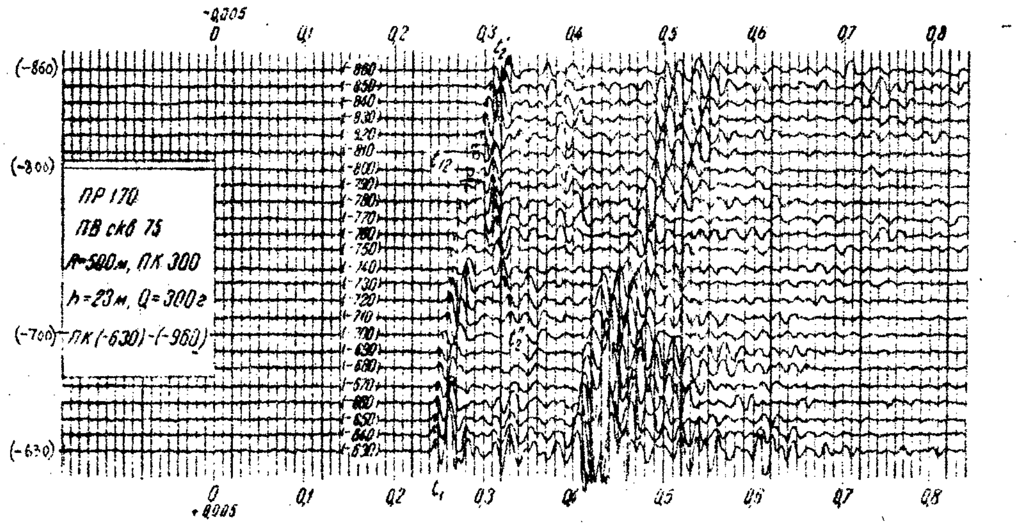


Fig. 50. Seismogram on which the interfering waves t_1 and t_2 are traced separately only on one side of the interference zone; t_{12} -- interference wave.

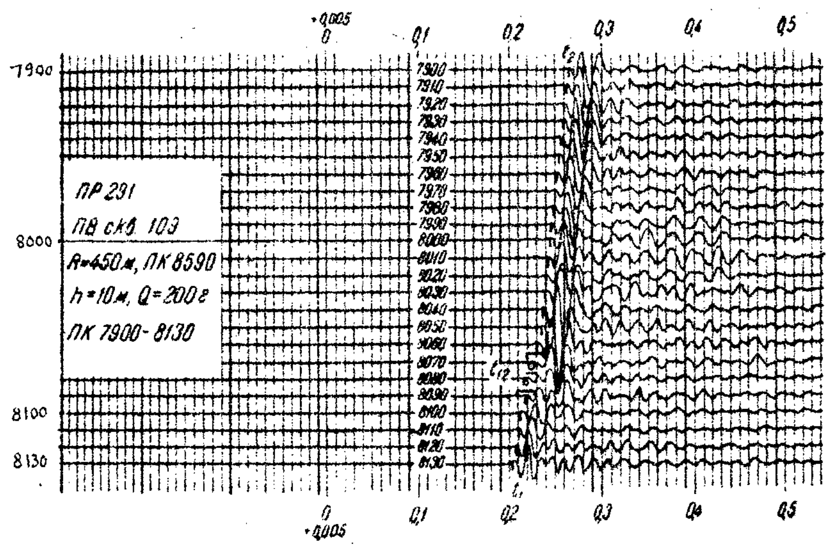


Fig. 51. Seismogram on which the interfering waves t_1 and t_2 cannot be separately traced on the same profile interval; $t_{1,2}$ -- interference zone.

of the waves is usually small.

The first case, when both waves can be separately traced on the recordings on both sides of the interference zone, is the simplest for the correlation of the waves. In this case, it is easy to establish where the interchange of the simple wave by the interference wave takes place and to determine the boundaries of the interference zone.

In the second case, when both waves are separated on the recordings only on one side of the interfering zone, it is possible to establish reliably the fact of the interference of different waves, but it is frequently difficult to establish the limits of the zone of interference and to ascertain which of the interfering waves is traced beyond this zone. In this case, as indicated in reference /56/, it is sometimes possible to effect an erroneous transition without discontinuity in the correlation from one wave to another.

In the third case, it is not always possible to establish even the fact of the existence of the interference zone. Oscillations in this zone can sometimes be erroneously correlated continuously, and the danger of going over from one wave to another in this case is even greater than in the second case. In some cases, an error of a different kind id possible: the interference zone of two waves can be taken to be a simple wave, corresponding to a different separation boundary. In the latter case, one can erroneously separate on the records three simple waves, the regions of registration of which are delineated on the profile lines.

In the absence of a region where both waves are separately registered on the same profile intervals, the interchange of a simple wave by an interference wave can in many cases be observed with the aid of the last four criteria for the detection of wave interchange. The recording of a wave in the interference has a characteristic feature in shape and amplitude (2) which makes it possible to distinguish the interference wave from the simple wave. The recognition and the delineation of the interference zone are carried out most reliably at considerable differences in the dynamic characteristics of the interfering waves even in the absence of considerable differences in the apparent velocities, and also at considerable differences in the apparent velocities even in the absence of sharp differences in the dynamic features of the waves. In the delineation of the interfering zones, it is very important to compare the recordings obtained at different positions of the explosion points (Sections 6 and 7).

The question of correlation waves in the interference zones themselves and of the identification of waves registered on both sides of the interfering zone, is considered in Section 2.

Detection of the Replacement of a Simple Wave by Another Simple Wave in the Absence of a Region of Joint Registra-

tion of Waves. In this case, the regions of registration of waves do not overlap, and there is only a "butting" of these regions (Figs. 46 and 47). The case considered is frequently encountered in the investigation of media which are close to vertically stratified, in the study of faults and tapering layers; it sometimes takes place also in the investigation of horizontally stratified media and media with inclined separation boundaries, and particularly under considering damping of waves with distance. In the study of media close to horizontally stratified, this case is frequently encountered in prospecting at small depths. In these cases, in the zone where geometrical considerations indicate that the traced waves should interfere with other waves, they are quite weak and are in practice missing from the recordings.

It must be noted that it is sometimes difficult to establish the borderline between this case and the third or second cases (p.109), since quite frequently one encounters in practice interfering zones of such small extent that the region of joint registration of the waves can be considered as practically missing (Fig. 51). The detection of the interchange of simple waves in which there is no region of joint registration should be based on all of those criteria which were indicated previously and experience in experimental works under different seismogeological conditions has shown that the use of dynamic features of wave records is of particularly great value, apparent velocities are not always connected with the interchange of waves; furthermore, frequently, the apparent velocities of two interchanging waves are close to each other.

2. Correlation of Waves in the Presence of Interference Zones

Interference zones of refracted waves are encountered under a great variety of cases of construction of the medium. Depending on the seismogeological features of the medium, the placement of these zones on the surface of observations and their dimensions differ in certain specific features. For example, in the case of media close to horizontally stratified, the interference zones of the waves may have a great extent, particularly in those cases when the apparent velocity of the interfering waves is nearly equal. The extent of the interference zones may sometimes reach several kilometers (Section 6). On the surface of observations, the boundaries of the interference zones are located at equal distances from the explosion points, at which the shooting is carried out. In the case of media close to vertically-stratified, and also in the presence of faults or tapering layers, the protruding zones have a small extent which frequently does not exceed several tens of meters; in the case of overtaking systems, the interference zones are observed on the same stations in which the seismographs are located (Section 7).

The correlation of the waves and the interference zones themselves and the identification of the waves registered on both sides of these zones are particularly significant when the interference zones are long.

In an examination of the singularities of the recordings in the interference zones, we shall assume that the predominating frequencies of the interfering waves are close to each other. We shall not consider the case of interfering waves of different frequencies, since it is encountered relatively rarely in practice, particularly in the investigation of sufficiently great depths ($H > 200$ meters).

Classification of Interference Zones by the Ratio of Intensity of the Interfering Waves. Experience in working with CMRW under different seismogeological conditions, and also calculations of theoretical seismograms have shown that in the examination of interference waves it is necessary to distinguish two cases:

1) when the interfering waves are characterized by approximately equal amplitudes, and

2) when one of the interfering waves is dominating in intensity, and its amplitude is not less than twice the amplitude of the other waves.

Interfering Waves with Different Amplitudes. In this case, one complex wave is registered in the interference zone. The shape of the complex wave may differ substantially from the shape of the component waves and frequently varies radically with changing distance from the explosion point. These sharp changes in the form of the record with distance, the appearance and the vanishing of additional extrema, alternating increase and decrease in the amplitudes, and also the considerable changes in the magnitude ofthe apparent velocity, all are characteristic of recordings of waves in the interference zone. In the case under consideration, it is usually impossible to separate in the complex oscillation the phases of its component waves. By way on an example, Fig. 52 shows a theoretical seismogram for the case when the amplitudes of the interfering waves are nearly equal.

In interferences of this type, it is possible to trace on the recordings only the phases of the complex wave. The apparent velocities, determined from the phases of the complex oscillation, frequently vary sharply within the interference zone, and their magnitudes may be either intermediate between the values of the apparent velocities V_1^* and V_2^* of the two interfering waves, as well as smaller than the smallest or greater than the greatest of the values of V_1^* or V_2^*.

In the case of horizontally stratified media, these distortions of the apparent velocities due to the interferen-

ce of the waves may cause a considerable deviation from parallel of the hodographs of the phases of the complex wave and the overtaken or overtaking hodographs of the phases of the simple waves.

In the case under consideration, it is necessary to stop the correlation of each simple wave in the interference zone and to trace only the phases of the complex vave. These phases must be plotted on a hodograph, in order to display the connection between the time of arrival of the waves before and after the interference zone; in quantitative interpretation, i.e., in plotting the section and determining the boundary velocities, one cannot use the region of the hodograph corresponding to the interference zone.

One Interfering Wave is Dominating. The form of the recording of the dominating wave remains almost unchanged in the passage through the interference zone, but against the background of the principal oscillation there appear certain complications (Figs. 49 and 53), connected with the superposition of oscillations of the weaker wave. In connection with the practically unchanged form of the dominating wave, it can be traced continuously through the interference zone. The correlation of the wave with small amplitude experiences a discontinuity in this zone.

It must be noted that in the case when there is a small difference in time of arrival of the two waves, the less intense wave sometimes cannot be separated in the region of time intervals greater than the time of arrival of the dominating wave. In particular, if both considered waves are registered on definite intervals of the profile as first waves, then the wave with the smaller amplitude frequently cannot be separated in the region of the subsequent arrivals (Fig. 54, wave t_2).

The apparent velocity of the dominating wave in the interference zone remains practically undistorted, in connection with which the hodograph of the wave in this zone is parallel to the overtaking hodograph of the same wave, traced ahead of its interference zone.

Identification of Waves Traced Ahead and Past the Interference Zone. In the discontinuity of the correlation in the interference zone, the question arises of identification of the waves that have been traced ahead of and past this zone. This question is of great significance for the correctness of further interpretation. It must be borne in mind that owing to the damping of the waves with distance, frequently the waves traced on the recordings ahead of the interference zone with other waves, are not traced past the interference zone.

In the multiple-layer medium, owing to the presence of a large number of separation boundaries, one can trace past the interference zone other waves which can erroneously be identified with the wave traced ahead of the interference zone.

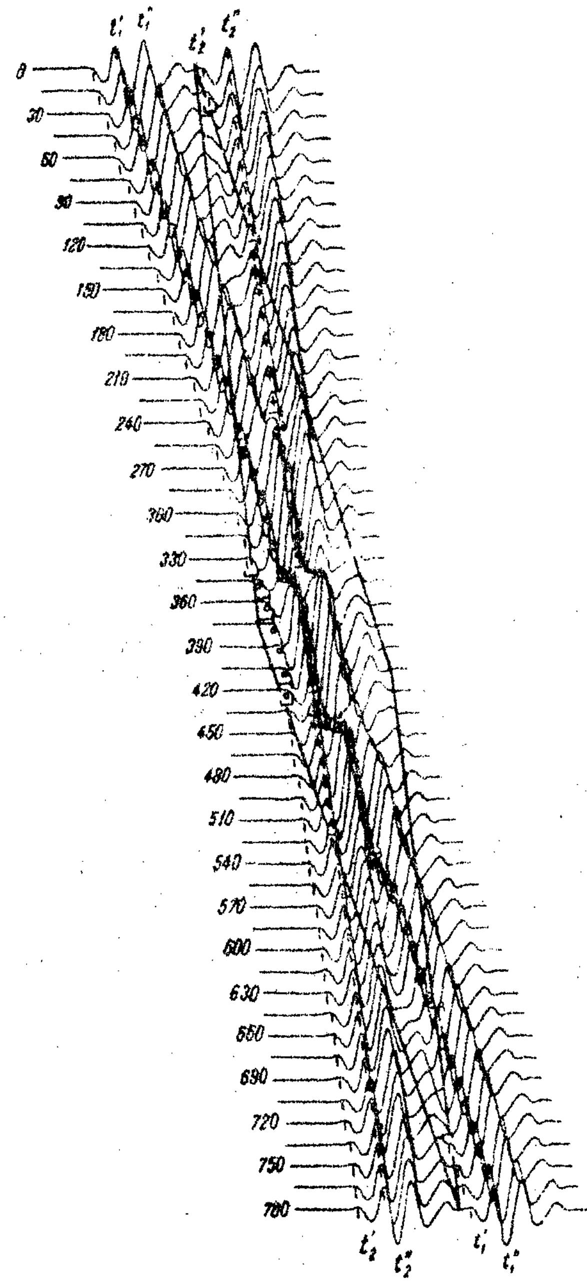


Fig. 52. Theoretical seismogram, plotted for the case when the amplitudes of the interfering waves t_1 and t_2 are nearly equal. The solid lines show the contours of the interference zone. The short strokes note the phases T_1', T_1'', ..., T_2', T_2'' of the simple waves, the circles indicate the phases of the interferance wave. The symbol ⌴ denotes the interchange of waves; the symbol ⊣ denotes an interruption in the correlation of the interference wave.

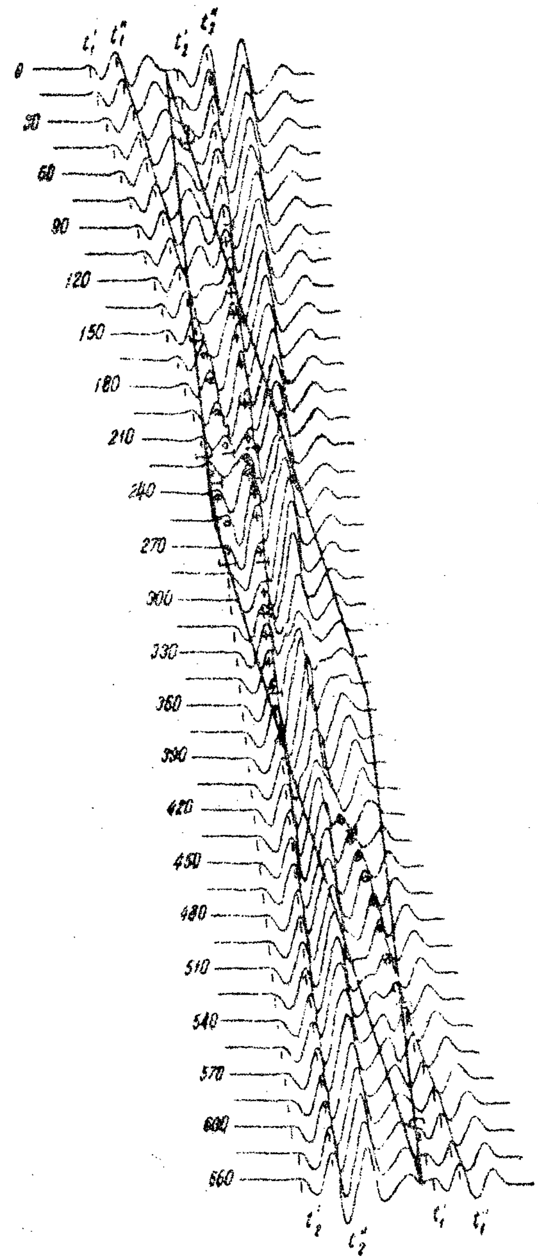


Fig. 53. Theoretical seismogram constructed for the case when the ratio of the amplitudes of the interfering waves t_1 and t_2 is equal to two. The solid lines show the contours of the interference zone. The short strokes indicate the phases t_1', t_1'', ..., t'_2, t_2'' of the simple waves; the crosses indicate the phases of the dominating wave, slightly distorted owing to the superposition of the wave t_1; the circles denote the phases of the interference waves; the symbol ⊔ indicates an interchange of waves; the symbol ⊣ indicates a discontinuity in the correlation of the interference wave.

In this connection, it is very important to establish a criterion for the identification of waves registered ahead of and past the interference zone. The principal criteria in this case are as follows:

1) parallelness of the hodograph of the wave, registered past the interference zone, to the overtaking hodograph of the wave registered ahead of the interference zone;

2) similarity in the shape of the recording on the seismograms obtained in the overtaking systems.

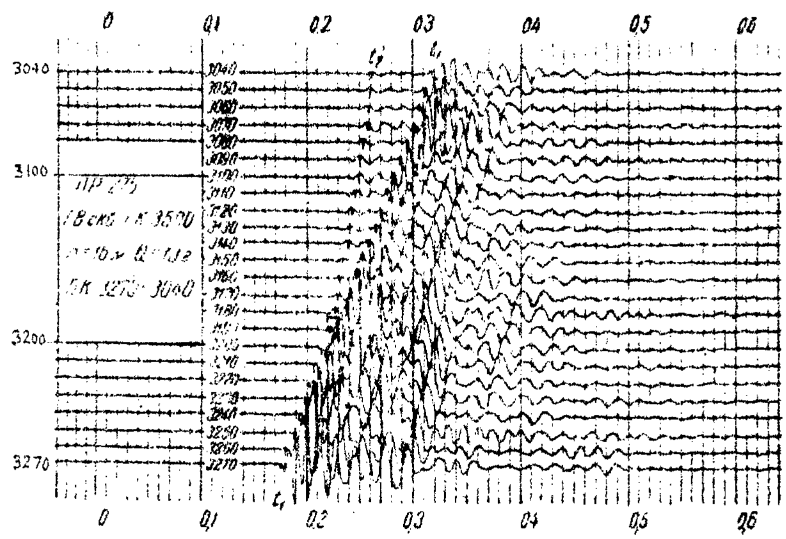


Fig. 54. Seismograms illustrating the interference of the dominating wave t_1 with a weaker wave t_2.

The first of these criteria, as shown by experiment, can always be used for identification of waves but it may be found to be insufficient in the study of a thinly laminated layer, in which there are several layers characterized by nearly equal values of the boundary velocity.

The second criterion cannot be used in certain cases for the identification of waves, since sometimes the waves do not have any characteristic features in shape of recording which would permit distinguishing them from the waves corresponding to other separation boundaries.

In particular, this is sometimes observed in the investigation of media in which there is a large number of thin layers with nearly equal velocities.

Thus, the use of the foregoing two criteria for the identification of waves registered on both sides of the inter-

ference zone raises difficulties principally only on the study of a multiple-layer medium, in which there are thin layers with practically equal velocities.

In all other cases, the identification of thw waves is usually reliable. We note that with the identification of the waves it is impossible in most cases to use the criterion of the ratio of the amplitudes of the considered wave and other waves since, owing to the fact that the different waves are differently attenuated with distance, this ratio may be quite different on recordings obtained within overtaking systems.

Particularly, the wave which is dominating on recordings obtained with a nearby explosion point may lose its dominating character on recordings obtained at a more remote explosion point. This is clearly seen from an examination of the recordings of the wave t_3 (Fig. 49), obtained at various distances from the point of explosion. Therefore, in the identification of waves registered on both sides of the interference zone, the amplitude symptoms play a considerably smaller role than symptoms of the shape of the recording and of the parallel nature of the overtaking hodographs.

3. Singularities of the Correlation of Waves at Different Types of Measurements

In was indicated in Chapter III that when working with OMRW the following principal types of measurements are made:

1) longitudinal profile measurements,

2) transverse profile measurement,

3) area survey with a single explosion point.

The correlation of waves in each of the indicated methods of measurement has certain specific features which we shall now stop to consider.

Correlation of Waves in a Longitudinal and Transverse Profile Measurement. In longitudinal profile measurements, the distances from the point of explosion to the seismographs change more when moving along the line of the profile than in transverse profile taking.

In this connection, the changes in amplitudes and details of the shape of the recording of waves are more clearly seen on seismographs obtained with transverse profiles than on

seismographs obtained with longitudinal profiles, since on transverse profiles these changes are hardly masked by the gradual reduction in the amplitude of the wave with increased distance from the point of explosion.

Consequently, the second and third criterion for the recognition of wave interchange -- change in form and change in amplitude of the wave -- can be used more frequently in the case of transverse profiles and more fully than in the case of longitudinal profiles.

The changes in the degree of damping of the waves with the distance and the changes in the apparent velocity at small changes of distance from the point of explosion to the points of observation can hardly be discerned on the records. Therefore, the fourth and fifth criteria for the recognition of wave interchanges -- changes in the degree of damping of the waves with distance or the change in the apparent velocity -- can be used in the case of transverse profile plotting to a lesser degree than in longitudinal profile plotting. On recordings obtained in longitudinal profiles, differences in the apparent velocities of the waves and in the degree of their damping with distance can be seen quite clearly, and they should be used in the correlation of waves. On recordings obtained on transverse profiles, these distances can be seen only when the points of observations are sufficiently remote from the region of minimum of the hodograph.

Thus, the changes in the form of the recordings and in the amplitude of the waves are more clearly seen on recordings obtained on transverse profiles, and the changes in the degree of damping of the wave with distance and with apparent velocity are more clearly seen on recordings obtained on longitudinal profiles. Fig. 55 shows two seismograms obtained in the study of a vertically stratified medium on one and the same section of the profile on longitudinal (Fig. 55a) and transverse shooting (Fig. 55b). On both seismograms, one sees one in the same wave interchange; the stations of the profile to which the changes are assigned differ little from each other through differences in the magnitudes of the drift of the rays to different placements of the explosion points. From an examination of these seismograms it is easily seen that the replacement of t_1 by wave t_2 is seen much more clearly by the amplitude feature on the recording obtained on the transverse profile; at the same time, the difference in the apparent velocities of the waves t_1, t_2, t_3 is more clearly seen on a recording obtained in a longitudinal profile.

It should be noted that the advantage of the transverse profiling with respect to the utilization of the peculiarities in the shape and amplitude of the recordings for purposes of correlation is particularly important in the investigation of vertically stratified media (Section 7). In the inves-

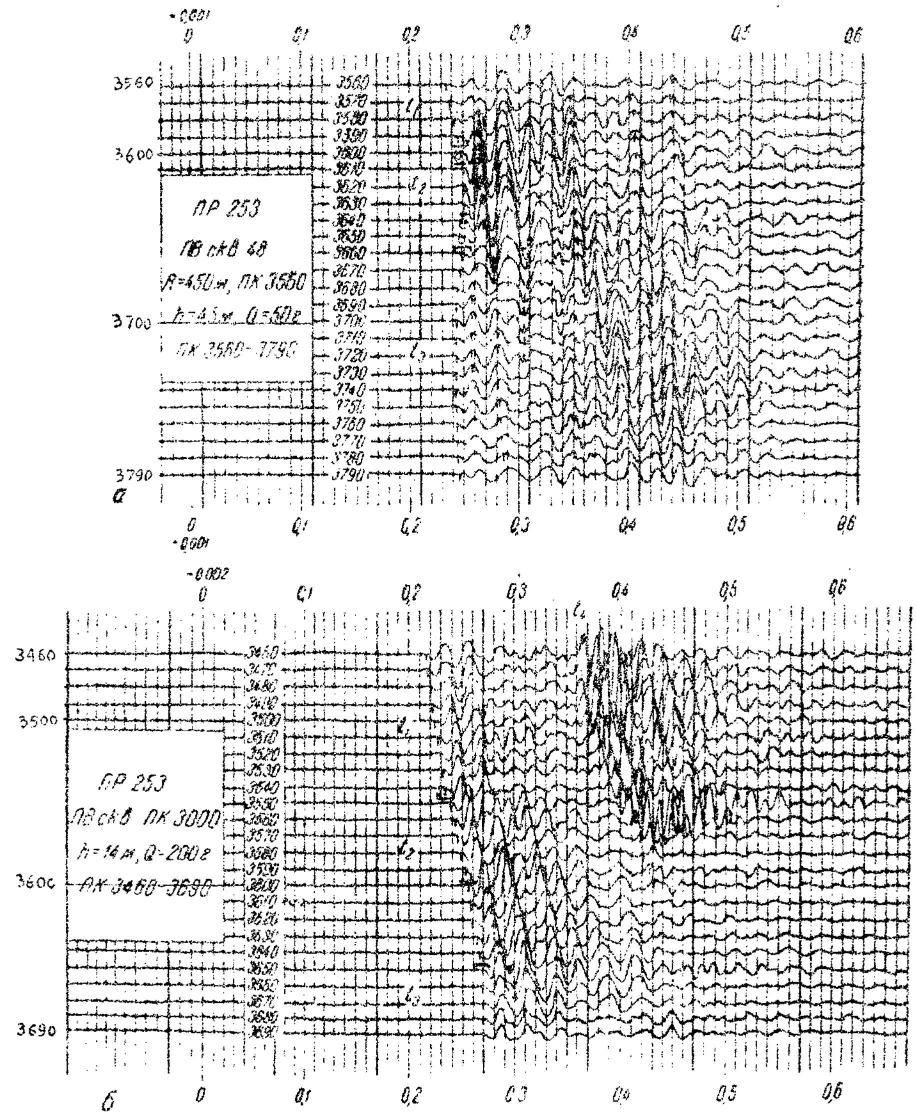


Fig. 55. Seismograms obtained on one and the same interval of the profile: in transverse (a), and in longitudinal (b) shooting.

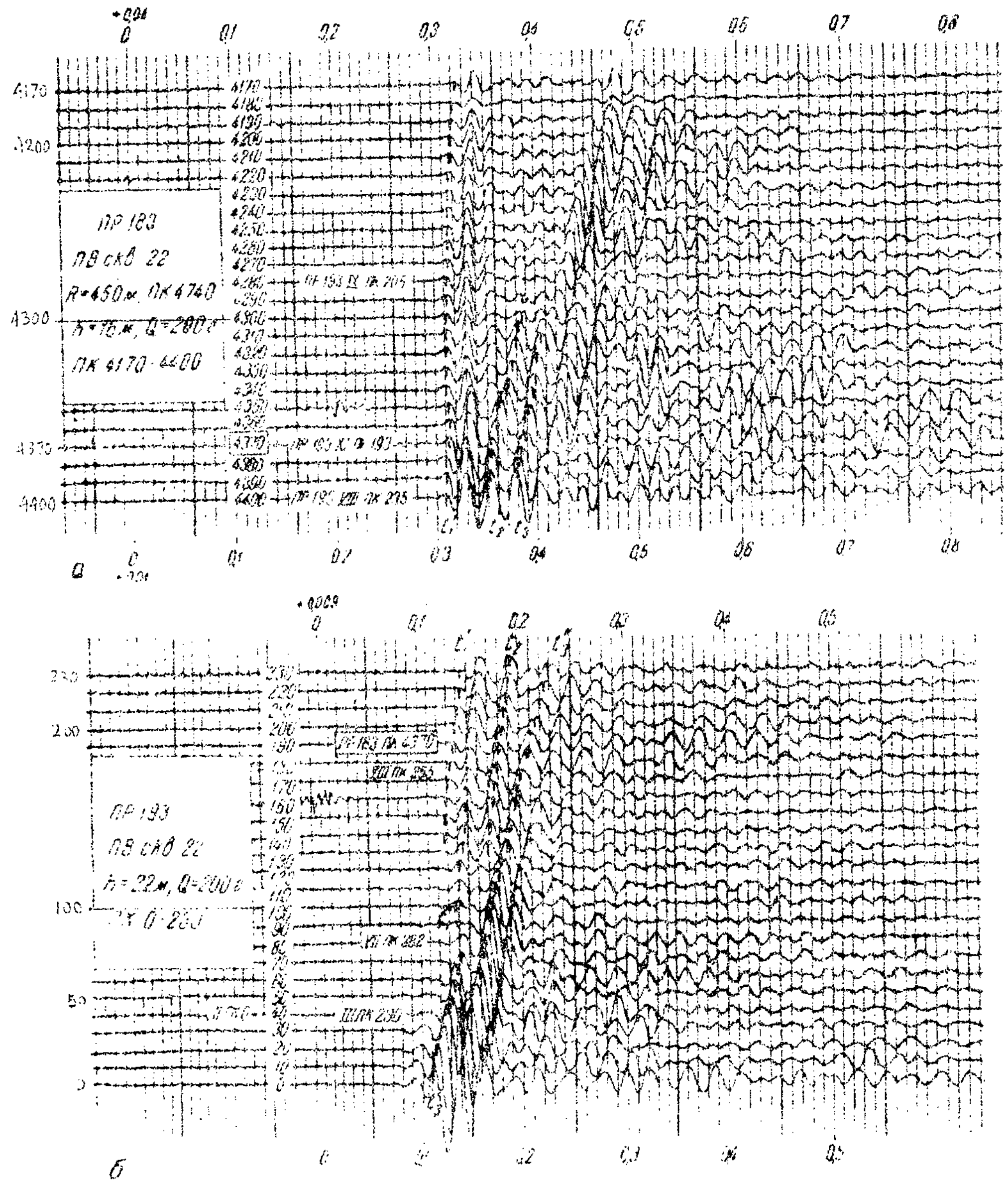


Fig. 56. Seismograms obtained at one and the same point of explosion by two intersecting profiles. The symbol 4370 indicates the station where the profiles intersect.

tigation of horizontally stratified media the transverse profiling is used to a considerably lesser extent and usually the distance from the point of explosion to the line of the profile is chosen so that the waves do not interfere with each other (Chapter III, Section 3).

However, even in the investigation of horizontally-stratified media one encounters relatively frequently wave interchanges corresponding to different separation boundaries and the regions of registration of these waves do not overlap. Such interchanges of waves can be reliably disclosed in transverse profiling by noting the changes in the form and amplitude of the recordings.

The advantage of the correlation of waves in longitudinal profiling over the correlation in transverse profiling lies in the fact that in longitudinal profiles the observations are usually carried out at several explosion points whereas in transverse profiles the observations are carried out with one explosion point. A comparison of the recordings obtained at different points of explosion facilitates considerably the correlation of the waves and makes it possible to disclose more reliably the interference zones and the zones of interchanges of simple waves.

On the Correlation of Waves in Area Surveys. In area surveys it is possible to make fuller use of the forefoing criteria for the separation and correlation of waves and for the exhibition of their interchanges than in a profile measurement of any type. The elements of the area measurement are usually transverse, longitudinal, and lateral profiles which are placed in different manners relative to the point of explosion. Consequently, on some profiles the waves must be registered with distances Δ from the point of explosion which change little, and in others with distances Δ which change considerably. This makes it possible to exhibit most fully all the dynamic and kinematic features of the waves and to take them into account in the correlation.

In area surveys, the waves are registered at the points of intersection of different profiles with equal distances from the point of explosion, but at different orientations of the profiles.

A comparison of the recordings obtained at different orientation of the profile makes it frequently possible to exhibit interchanges of waves which cannot be detected for a single profile orientation, and makes it possible to establish whether it was one wave that has been recorded or a complicated oscillation which is a result of the interference of several waves.

By way of an example, Fig. 56 shows recordings obtained in area measurement based on two intersecting profiles. On seismogram a, at the initial portion of the recording, one clearly sees two waves t_1 and t_2, the in-phase axes of which

have different inclinations. On seismogram b, the in-phase axes of the waves are parallels and they can be assumed erroneously as the phases of one in the same wave. In this case, as in many other cases encountered in practice, area measurement makes it possible to establish the mutual relationships between different waves and to determine the directions of their approaches.

The principal advantage of correlation of waves in the case of area survey for one common point of explosion, over the correlation of waves in profile measurement -- is the possibility of reliable control of the correctness of the correlation by correlating waves over close contours/18/. If at a certain point of the contour a definite phase of the investigated wave has been separated, then as a result of going around the contour it is necessary to arrive at the same phase. If this is not fulfilled then, consequently, in some part of the contour the observer has moved over in error during the correlation to a different phase of the same wave or to a different wave. As a result of a thorough examination of all the recordings, obtained along a closed contour, and as a result of the analysis of the causes of the violation of correlation, it is possible to disclose interchanges of simple waves and zones of wave interference which were omitted in the initial circuit around the contour. In profile measurement such a control over the correctness of the correlation is lacking, and therefore in some cases the interchanges of waves can be omitted during the correlation.

It must also be noted that in the correlation of recordings obtained in area measurement, it is sometimes considerably easier to ascertain in some cases what discontinuities in the correlation are connected with wave interchange and which are connected with local changes in the properties of the surface layer, and trace a contour around such local zones.

4. On the Correlation of First Waves

<u>On the Advantages of Correlation of Waves Registered as First Waves</u>. The correlation of refracted waves registered as first waves as indicated in references/16,24/, can be carried out more simply and more reliably than the correlation of subsequent waves. This is due to the following causes:

1) in the initial portion of the seismograms, the background of a regular noise, due to the explosion, is considerably less than in the subsequent portion of the seismogram;

2) in the investigation of layered media, the waves which are traced in the succeeding portion of the seismogram are frequently

separated by small intervals of time from the other regular waves, with which they interfere to one degree or another.

These interference phenomena frequently prevent the separation of simple waves particularly in those cases when these waves have low intensity compared with other dominating waves. In the initial portion of the recording, interference phenomena play a considerably smaller role than in the subsequent part of the recording, and they can be more readily observed than in the subsequent portion of the seismogram, and this facilitates the separation and the tracing of the simple waves.

An important consequence of the foregoing two singularities of tracing of waves in the initial portion of the recording is the fact that waves at small amplitudes which frequently cannot be separated in the region of subsequent arrivals from the background of a regular noise or because of interference with other more intense waves, can be reliably separated and traced in the region of the first arrivals. This circumstance is of great significance, particularly in the study of surface crystal rocks, since sometimes the refracted waves corresponding to the surface of the crystal rocks is characterized by low intensity, and it is impossible to separate in the region of subsequent arrivals this wave from the background of intense oscillations of waves that correspond to a separation boundary in sedimentation rocks. In the region of first arrivals this weak but stable wave can be reliably separated on the recording (Fig. 54b, wave t_2) and followed over a great distance.

<u>On the Correlation of First Waves Under Conditions of Their Strong Damping</u>. Frequently, the waves registered as first waves on the recordings are strongly damped with distance, and starting with a certain distance from the point of explosion, they can no longer be separated on the recording. In certain cases, if the charge is considerably increased, the first waves nevertheless can be separated from the recording but upon increasing distance from the point of explosion the records of such waves cannot be obtained in legible form. By way of an example, Fig. 57a and b shows the recording obtained on one and the same station at different charges. On seismogram c was obtained at a greater distance from the point of explosion, and on it one cannot separate the first wave t_1, in spite of the fact that the sensitivity of the apparatus has been increased to such an extent that the background noise is visible.

On recordings of the type shown in Figs. 57a and c, the first waves may be erroneously assumed to be the waves which actually are subsequent waves. In such cases, a thorough correlation of the waves on the seismograms and a delineation

of the regions of registration of different waves are of particularly great significance. If the different waves which appear to be first ones in time of arrival on different sections of the profile, are assumed to be one and the same wave and continuously correlated, quite incorrect conclusions can be drawn regarding the structure of the media. Let us dwell on the analysis of the features of recordings at different ratios of the apparent velocities of the waves and let us consider the possible errors in their interpretation.

<u>Different Ratios of Apparent Velocities of First Waves Under Conditions of Their Strong Damping.</u> Depending on the seismogeological structure of the medium, three different cases are possible of a ratio of apparent velocities V* of a damped first wave t_1 and subsequent wave t_2, which may be assumed to be the first in time of arrival:

1) $V^*(t_2) \quad V^*(t_1)$,

2) $V^*(t_2) \quad V^*(t_1)$,

3) $V^*(t_2) = V^*(t_1)$.

1) Case $V^* (t_2) > V^*(t_1)$.

This case is frequently encountered in the study of stratified media with horizontal and inclined separation boundaries. As this ratio of the apparent velocities, wave t_1, at a certain distance l from the point of explosion, is actually registered as the first wave but this distance is greater than the distance Δ, starting with which a certain wave t_2 can be assumed to be the first wave, owing to the strong damping of wave t_1 (Fig. 58). The hodograph of the first wave, constructed on the basis of the correlated waves, has a form which is typical for a stratified medium when the laws of geometric seismics are observed, i.e., the waves appearing at greater distances from the point of explosion are characterized by greater apparent velocities than the waves registered at shorter distances from the point of explosion. The feature of this hodograph is that the hodographs of the waves that are successively replacing each other do not intersect, whereas in some cases the displacements of the branches of the hodographs along the time axis may be relatively large.

2) Case $V^* (t_2) < V^*(t_1)$.

Such a ratio of apparent velocities of registered waves is observed if the structure of the medium includes a screening layer with a velocity which is increased compared with the velocities in the lower layers. It has been shown experimentally in reference /10/ that if the screening layer is characterized by a thickness h, smaller than the wavelength λ incident on its surface (h/λ = 0.06 to 0.50), then first of all in spite of the laws of geometric seismics, refracted waves are produced corresponding to the lower layers with decreased velocities; secondly, the refracted waves corresponding to the screening layer of low thickness are rapidly damped with distance. Therefore, starting with a certain distance, the wave t_2 (Fig. 57a, Fig. 59), corresponding to a screening layer, has the same appearance on the recordings as a first wave. The hodographs of the first waves have in this case a form analogous to that shown in Fig. 115.

In this case, it is necessary to have particularly careful correlation of the waves since in the absence of a complete system of observations the recordings in the hodograph of this type may erroneously be ascribed to a sharp immersion of one in the same boundary.

3) Case $V^*(t_2) = V^*(t_1)$.

This case is encountered in the investigation of

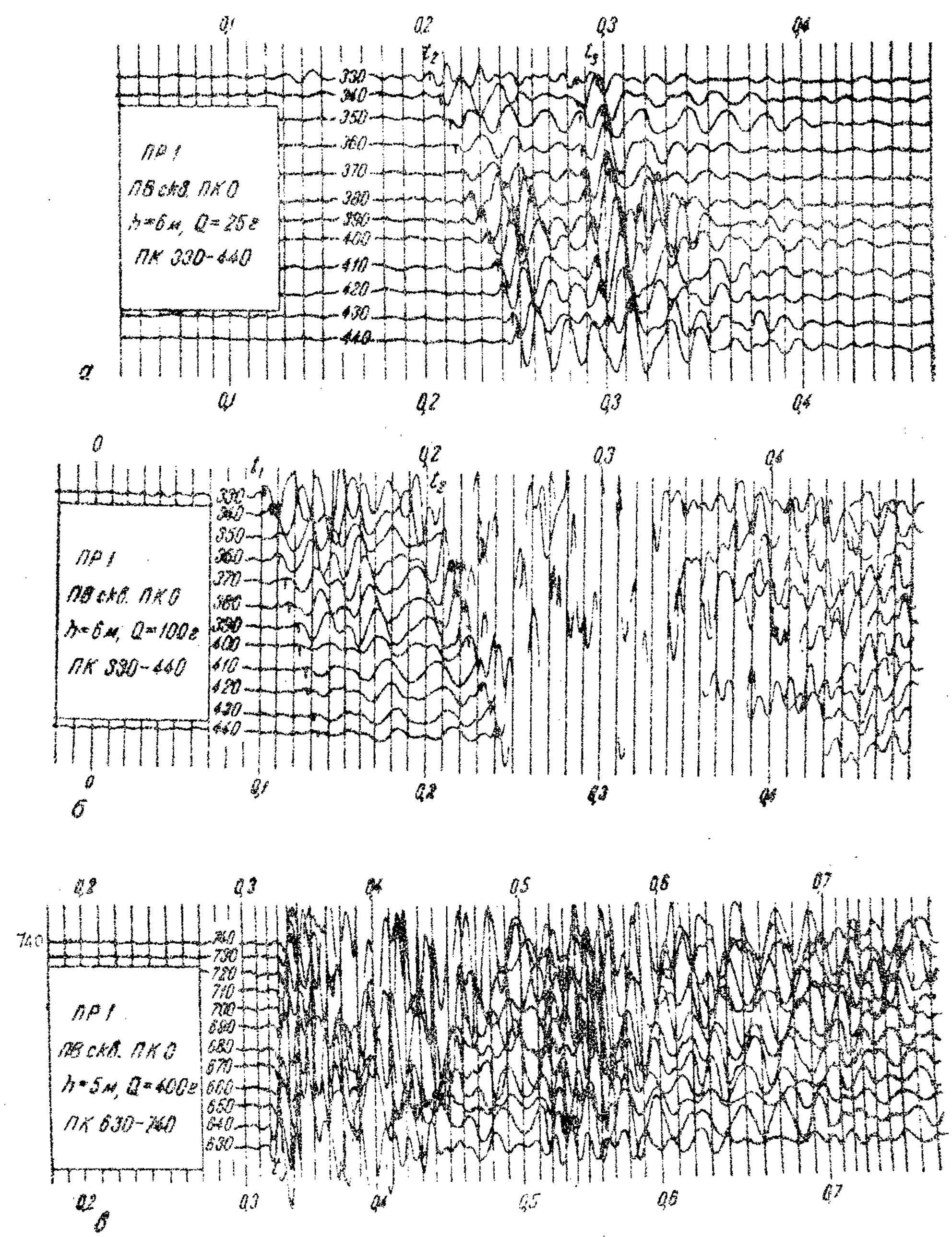


Fig. 57. Seismograms which illustrate the damping of first waves with distances.
a, b -- seismograms obtained on one and the same station at different charges.
c -- seismograms obtained at greater distances from the point of explosion.

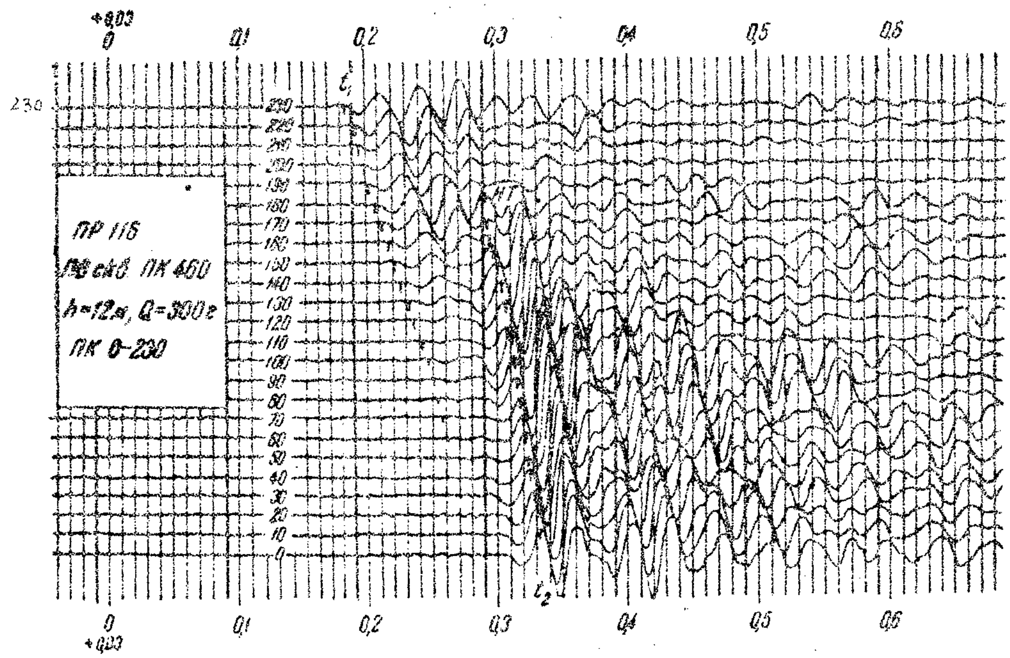


Fig. 58. Seismograms on which is registered a damped first wave t_1 with smaller apparent velocity than the succeeded wave t_1

media in which there are relatively thin layers with increases by practically equal velocities. In this case, as also in the second case considered above, a deviation takes place from the laws of geometric seismics. When the wave is incident at the limiting angle on the boundary of the upper refracting layer, part of the energy passes through this layer and gives rise to refracted waves, corresponding to the lower layers. Thus, in spite of the laws of geometric seismics, the lower layers are not shielded by the upper thin layers which are characterized by the same values of velocity.

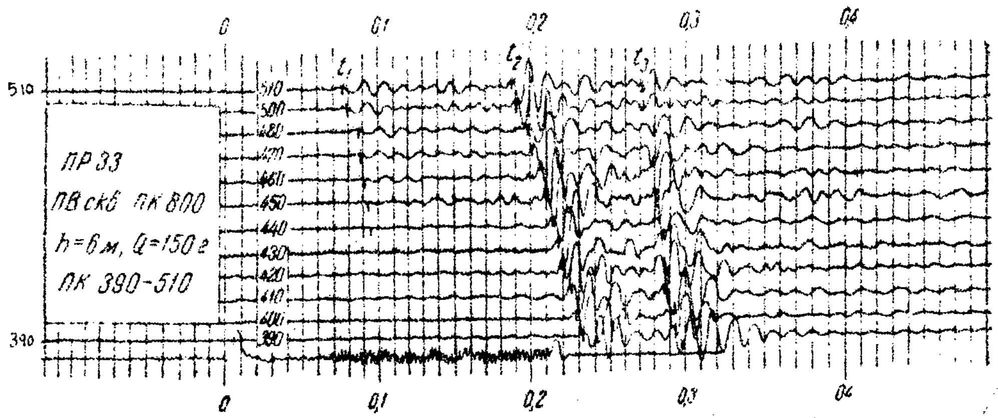


Fig. 59. Seismograms which illustrate the damping of the wave t_1 corresponding to a thin screening layer, with distance. Wave t_2 corresponds to the screened layer.

In this case, the in-phase axes of the waves on the seismogram are practically parallel (Fig. 60) and consequently the hodographs based on them are also parallel.

Frequently, some of the waves are damped more rapidly with distance than others, as a result of which the parallel branches of the hodograph have a different extent. In particular, on the seismogram of Fig. 60, wave t_1 attenuates more rapidly with distance than wave t_2.

The parallel nature of the hodographs of the first waves can lead in some cases, particularly if the waves are insufficiently well resolved on the seismogram, to a false conclusion that the constructed hodographs represent hodographs of phases of one and the same wave. Therefore, in the correlation of waves it is necessary to pay particular attention to the delineation of the regions of registration of different waves. A solution of this problem must be based principally on the examination of the dynamic characteristics of the waves -- on a

comparison of their intensity and on the examination of the degree of their damping with distance.

The experience of the Geophysics Institute in different regions has shown that the curves that show the dependence of the amplitude on the distance, plotted for different phase of one and the same wave, are practically parallel with rare exceptions, whereas curves constructed for different waves, frequently differ substantially from each other. Therefore, pronounced differences in the degree of damping of the traced waves with distance, under insufficiently good resolution of the waves on the recording, may be used to resolve the problem of whether the registered prolonged oscillation corresponds to one or to several waves.

5. Finding the Initial Points on the Records of Refracted Waves

The finding of the initial points on the records of refracted waves plays an important role in the CMRW for the following reasons:

1) the determination of the initial points helps establish the limits of the region of existence of different refracted waves, which is quite important for further interpretation;

2) the coordinates of the initial points of the hodographs of the refracted waves can be used to determine the average velocities up to the refracting boundaries (Chapter V, Section 3).

On the basis of the experience gained with the CMRW under different seismogeological conditions, it has been established that different cases of separation of the initial points on the recordings can be subdivided into the following two categories:

a) one registers the refracted and reflected waves, corresponding to one and the same separation boundary /42/;

b) one registers only the refracted waves, and the reflected waves corresponding to the same separation boundary are missing.

Let us examine the question of the dynamic peculiarities of the recordings which make it possible to display the initial points in the foregoing two cases.

On the Separation of the Initial Points in the Presence of Refracted and Reflected Waves Corresponding to One and the Same Separation Boundary. In the delineation of the regions of registration of refracted and reflected waves, corresponding to

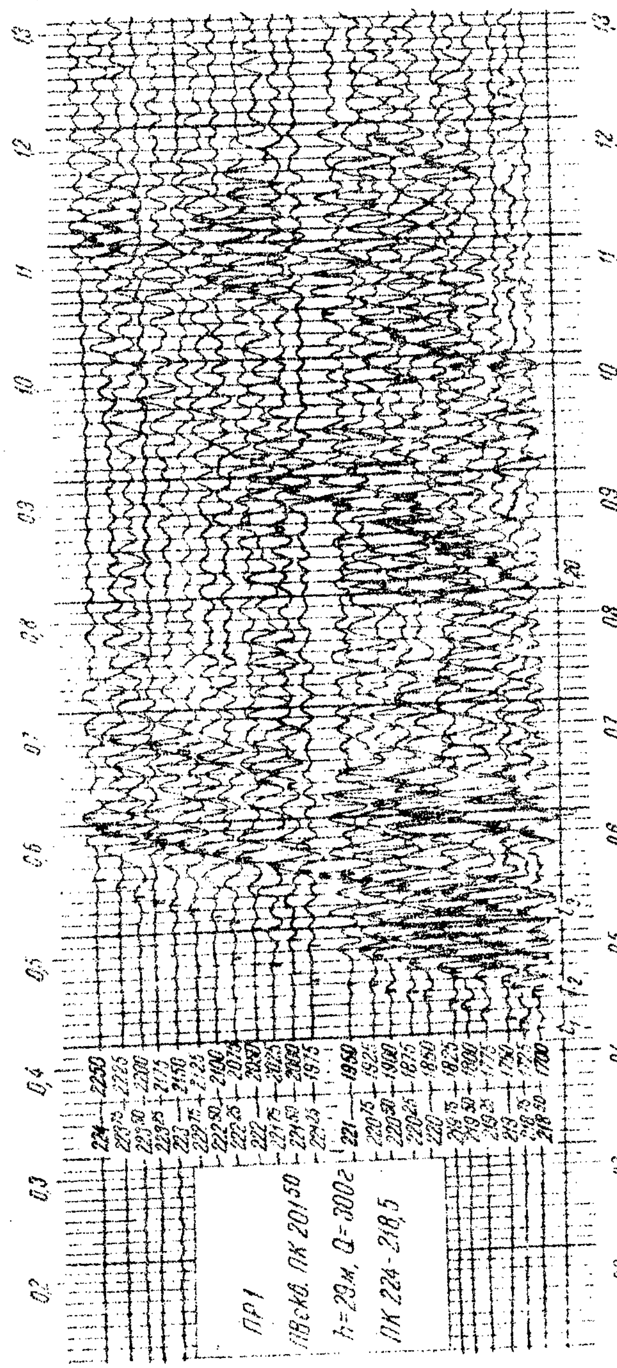


Fig. 60. Seismograms on which are registered waves t_1, t_2 and t_3 with parallel in-phase axes.

the same separation boundary, the following three cases are encountered:

1) interchange of the reflected waves by a refracted wave accompanied by a sharp change in the dynamic features of the records, on the basis of which it is possible to establish with sufficient accuracy the position of the initial point;

2) in the region of the replacement of the reflected wave by the refracted wave there takes place a gradual change in the dynamic features of the wave; in this case, it is possible to oscillate on the recordings the region where the initial point is located, but the position of this point cannot be established;

3) the replacement of the reflected by the refracted one is not accompanied by dynamic singularities in the records, and in the correlation of the seismograms it is impossible to separate not only the position of the initial point, but even the region where it is located.

<u>Case 1</u>. The principal dynamic features which are observed in the interchange of a reflected wave by a refracted wave are as follows:

1) change of form of the recording without a noticeable change in the predominant period and the duration of the oscillation;

2) increase in the duration of the pulse -- appearance of earlier or later phases of oscillations;

3) increase in the predominating period;

4) increase in the intensity; only in relatively rare cases can one note on the recordings simultaneous changes of the period, duration of the oscillations, details of the outline of the recording, and the amplitude. For the most part, one notices on the recordings only one or two of the foregoing symptoms, most predominantly the latter two.

Fig. 61 (a) shows an example of the recording on which the initial point is clearly identified by the increase in the amplitude and by the appearance of earlier phases of oscillations. The sharp increase in the amplitude upon replacement of the reflected waves by the refracted wave is seen particularly clearly upon comparison with the wave t_1, which is damped with increasing distance from the point of explosion.

<u>Case 2</u>. In the region of transition from the re-

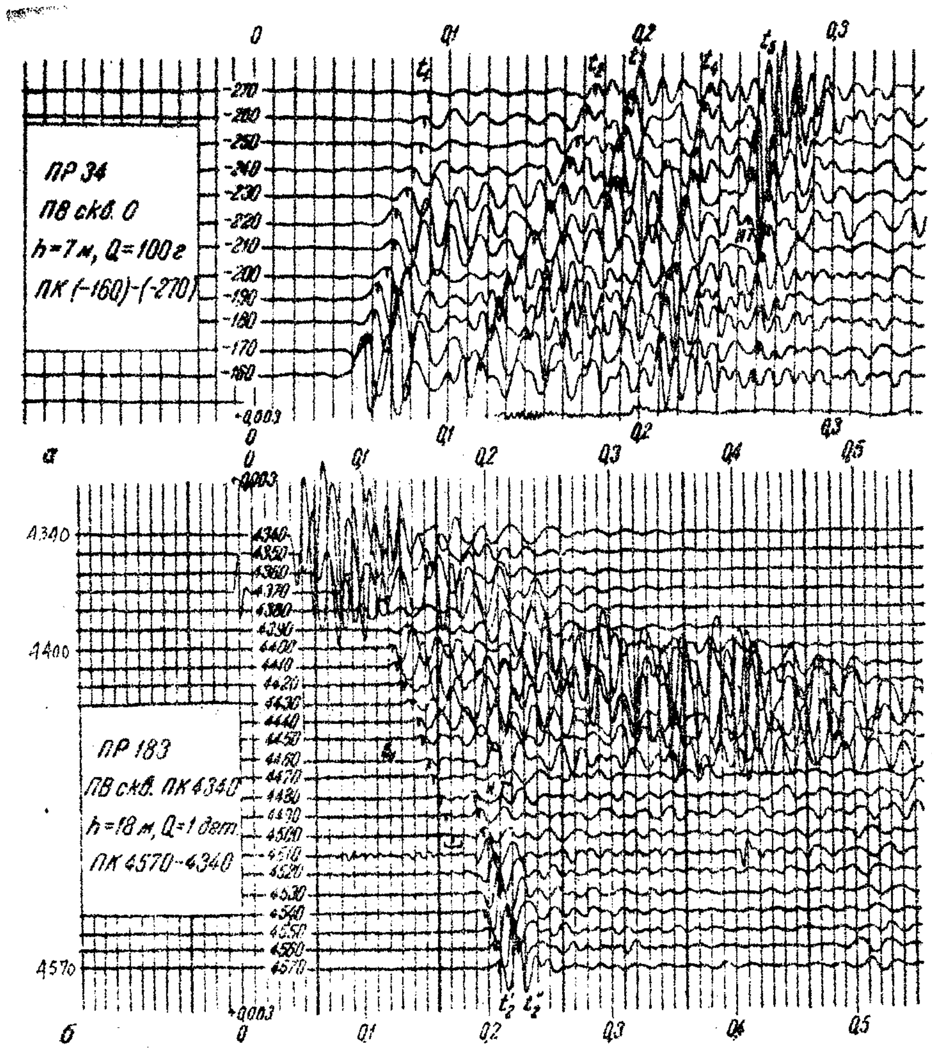


Fig. 61. a - Seismogram on which the replacement of the reflected wave by the refracted wave (t_5) is noted by the dynamic features of the recording; b - seismograms on which the initial point of the wave t_2 can be noted.

flected wave to the refracted wave one observes a gradual increase in the amplitude; the amplitude reaches a maximum past the initial point in the region of registration of the refracted waves, and then diminishes smoothly with increasing distance from the point of explosion. To determine the initial points of this type, it is necessary to have control over the sensitivity of the apparatus.

In some cases in the region of initial points one observes also a gradual increase in the period. The predominating period on the recordings are usually somewhat greater in the region of registration of refracted waves than in the region of registration of reflected waves, but the change in the periods is frequently so smooth that it cannot be observed directly from an examination of the seismograms and requires special measurements.

Case 3. In the region where the reflected wave is replaced by the refracted wave no changes are observed at all in the dynamic characteristics of the waves. In these cases, the position of the initial point can be established only from kinematic identification with the aid of the criterion that the overtaking hodographs must be parallel (Chapter V, Section 2). In some cases, particularly at small differences in the velocities in the covering medium and along the refracting layer, the position of the initial points cannot be established on the basis of an examination of the seismograms and the hodographs constructed from them, for at a sufficiently large distance from the point of explosion the overtaking hodograph of the refracted wave is practically parallel to the overtaking hodograph of the reflected wave. In these cases, the position of the initial points can be determined only by plotting the section (Chapter IX, Section 5).

The experimental data obtained by the Geophysical Institute show that one encounters most frequently the third case and most rarely the first case.

Frequently for one and the same separation boundary, at one position of the explosion point one observes distinct dynamic features of the recordings in the vicinity of the initial points, while at other positions of the point of explosion the initial points cannot be separated on the recordings. The question of the dependence of the dynamic singularities of the initial points on the seismogeological structure of the medium is still unclear to the present day and requires a special study.

The practice of the Geophysical Institute shows that cases when the refracted and reflected waves corresponding to one and the same separation boundary would be separated simultaneously on the recordings past the initial point are rare exceptions. Frequently, in the region of time where according

to the laws of geometric seismics reflected waves should be registered, the intensity of the recorded oscillations is quite small and therefore it is impossible to assume that the reflected waves are masked by other oscillations.

Apparently, the reflected waves have quite a small amplitude in this case, not exceeding the amplitude of the noise background. These experimental data are in good agreement with the results of the theoretical investigations of L. P. Zaytsev and N. V. Zvolinskiy (Chapter I) /39/.

On the Separation of the Initial Points in the Absence of Reflected Waves Corresponding to the One and the Same Separation Boundary. Frequently, there are registered on the charts waves which are refracted on the separation boundaries, which are not reflecting. In these cases, the initial points of the refracted waves are determined from the appearance of intense oscillations on the recordings which frequently are seen against a quiet background (Fig. 58 and Fig. 61b). Sometimes, the amplitude is small at the initial point, but upon further increase from the point of explosion it increases rapidly to a maximum after which it starts diminishing with distance.

In some cases, the wave is masked by noise in the region of the initial points of refraction, for example by surface waves or by refracted and reflected waves, corresponding to other separation boundaries. In these cases, the point of emergence of the refracted wave from the interference zone with other waves can be erroneously taken to be the initial points. Therefore, in solving theproblem whether the point under consideration is the initial one, it is necessary to examine very carefully the recordings and to assign reliably to the initial points only those at which the appearance of the reflected waves takes place against a quiet background and when this wave is not preceeded by another intense wave separated from it by a small time interval.

Experience shows that cases when only refracted waves corresponding to some separation boundary are registered, and reflected waves are missing, are quite frequent, particularly in the investigation at low depths -- up to 100 meters. The initial points of waves in these cases can be separated relatively rarely, owing to superposition of intense waves corresponding to other separation boundaries, and als owing to irregular noise.

Finally, frequently the refracted waves corresponding to certain separation boundaries can be registered only in the region of first arrivals and they cannot be separated in the region of subsequent arrivals; in particular, this takes place when the refracted waves have low intensities. In these cases, the initial points of the waves can in general not be separated on the recordings.

6. On the Correlation of Waves in the Case of Media which Are Nearly Horizontally Stratified

The Character of Seismic Recordings in the Case of Horizontally-Stratified Media. In the case of media which are nearly horizontally stratified, one can usually separate several refracted waves on the seismic records. Depending on the velocity characteristic of the medium, different relations are possible between the apparent velocities of the registered waves.

In the case of sharp velocity differentiation of the medium, the apparent velocities of the waves differ greatly from each other (Fig. 59). In the case of weak velocity differentiation of the medium, the apparent velocities of the waves differ little. Finally, in the study of sedimentation rocks, one frequently encounters cases when the investigated medium consists of intermittent relatively thin layers with increased and decreased velocities. In this case, as indicated in Section 4, several waves can occur corresponding to different thin layers with increased velocity. With this, if the velocities in the thin layers are close to each other, one can register on the seismograph several waves with practically parallel in-phase axes (Fig. 60).

Zones of Interference of Refracted Waves in the Case of Horizontally-Stratified Media. The refracted waves corresponding to different separation boundaries interfere with each other at definite distances from the point of explosion. In the zone of interference, theoscillations of one of the waves are superimposed on the oscillations of another wave and form one complex interference oscillation. The distance from the point of explosion to the start of the zone of interference of two waves depends on the difference of the depths in both refracting boundaries, on the differences in the magnitudes of the boundary velocities and layer velocities in the media covering both separation boundaries and also on the duration Δt of the oscillations of each of the waves.

If the average velocities in the covering media remain constant, the distance from the point of explosion to the start of the interference zone increases with increasing difference between the depths of the refracting boundaries, and with diminishing difference in the corresponding boundary velocities, and also with diminishing duration of oscillations of each simple wave. The extent of the interference zone of two waves is the greater the smaller the differences in the apparent velocities of both interfering waves and the longer the duration of their oscillations. Table 5 gives examples of the extent of the interference zone of two waves in the case of sharp and relatively weak differences in the apparent

velocities. In the calculations we determine the distance between points a and b of the observation lens, at which one of the waves begins at the instant when the oscillation of the other waves ceases. In the interval between points a and b, one of the waves begins before complete cessation of the oscillation of the second wave, and consequently, the waves interfere with each other.

Table 5

Serial #	V_1, in m/sec.	V_2, in m/sec.	Duration in Δt of the oscillations secs	Extent of the interference zone, meters
1	2500	5000	0,04	400
2	2500	3000	0,04	1200

The first case indicated in Table 5 is encountered in particular in the case of interference of a wave corresponding to a surface of crystal rocks with a wave corresponding to a separation boundary of a sedimentation layer above it (Fig. 49). The second case is encountered in the interference of waves corresponding to different separation boundaries in the sedimentation thickness at relatively small differences in the limiting velocities. Waves with such differences in the apparent velocities, or even with smaller ones, if separated by small time intervals, can frequently be traced under the conditions of interference phenomena over quite a long extent, sometimes over the extent of several kilometers (Fig. 114). As a result, one can frequently trace a complex interference oscillation over the entire length of the profile.

The geometric dimensions of the interference zone in the case of horizontally-stratified media are frequently less than follows from calculations, based on the magnitudes of the apparent wave velocities. This isconnected with the fact that the refracted waves corresponding to different separation boundaries attenuate to a different degree with distance. In particular, in some cases the waves corresponding to layers with nearly equal boundary velocities are characterized by a different degree of attenuation with distance. Because of the attenuation of one of the waves, only one simple wave is actually traced at distances from the explosion where both waves, judging from the magnitudes of the apparent velocities, should form one complex interference oscillation.

The difference in the degree of damping of the refracted waves with distance facilitates the correlation of the

waves in the investigation of media witl small differences in boundary velocities.

<u>Location of Interference Zones and Interchanges of Simple Waves Relative to the Point of Explosion.</u> The distinguishing feature of the correlation of waves, in the case of media which are close to horizontally-stratified, lies in the fact that the interference zones of the waves and the interchanges of the waves corresponding to different separation boundaries are observed approximately at equal distances from different explosion points.

With this, the dynamic features of the same waves registered at equal distances from different explosion points, are similar in the majority of cases, provided there are no substantial differences under the condition of excitation of the oscillations.

<u>Singularities of the Correlation of Refracted Waves in Observation on Longitudinal Profiles.</u> In connection with the fact that in the case of media which are close to horizontally-stratified the interference zones and the zones of interchanges of simple waves are located at equal distances from the point of explosion, it is necessary in the correlation of the waves to compare records obtained for different explosion points at identical distances from these points. In some cases, this makes it possible to determine more accurately the position of the regions where the waves interchange, and the contours of the interference zones.

The identification of the waves registered in opposing systems is usually carried out reliably on the basis of a correlation interrelation by mutual points.

The identification of waves registered in the same interval of profile with overtaking systems of observations can be carried out primarily on the basis of parallel in-phase axes of different waves, and consequently, on the basis of parallel overtaking hodographs.

We note that this criterion is not always sufficient for the identification of waves obtained in overtaking systems, in connection with the fact that in a sedimentation region, as indicated above, one frequently encounters thin layers with nearly equal boundary velocities. The dynamic features of the waves registered in overtaking systems are similar in the case of refracting layers which have a considerable thickness, and are characterized by weak absorbing properties. In the case of relatively thin layers, and also in the study of thick layers which are characterized by strong absorption, the dynamic features of the recordings obtained in overtaking systems may be different.

Considerable difference may also take place in the amplitude features of the waves: waves which appear to dominate on the recordings obtained for a nearer point of explosion

frequently lose the dominating character on recordings obtained at a more remote point of explosion.

From an examinatôn of the features of the identification of waves in overtaking systems it follows that it cannot always be reliable. Therefore, theprincipal correlation interrelation of the waves must be carried out by using opposing systems. The correlation interrelation of waves by means of overtaking systems should be considered as auxiliary and can be of independent significance principally in those cases when one registers the small number of waves, having characteristic dynamic features and different apparent velocities.

Singularities of the Correlation of Refracted Waves in Observations on Transverse Profiles. In the case of a horizontally-stratified medium the waves corresponding to different separation boundaries are characterized by a stable form of recording. In the region of the minimum of the hodograph, the apparent velocity of each of the waves is close to infinity.

In the case of a large boundary velocity in the refracting layer, the region of the minimum of the traverse hodograph may be quite extensive, and therefore the principal criteria for the detection of an interchange of waves are the changes in the form and amplitude of the wave. The change in the damping of the wave with distance and a change in the apparent velocities in the case of a horizontally-stratified medium may be difficult to disclose on the recordings obtained with transverse profiles. In this connection, the foregoing criteria to a lesser degree in the correlation of waves.

The zones of interference of refracted waves on transverse profiles may be quite extensive. Frequently, these waves are observed over the extent of the entire length of the profile. It is therefore necessary to choose distances from the point of explosion to the transverse profile and the length of the profile in such a manner that the waves which are of interest for the solution of the imposed prospecting problem can be traced outside the zone of their interference with other waves (See Chapter III).

7. Correlation of Waves in the Case of Media Close to Vertically Stratified.

The Character of Seismic Records in the Case of Vertically Stratified Media. If the vertical or steeply inclined layers are located under covering rocks (Fig. 62), then the records show refracted waves corresponding to the separation boundaries d_1, d_2, ..., in the covering medium, and the refracted wave correspondig to the surface ℓ of the layers

with different elastic properties. In some cases, owing to the damaged condition of the upper part of the vertically-stratified media, the wave propagates along the boundary m, located within this medium and usually relatively close to its surface λ. Henceforth, we shall speak, to simplify the arguments, of propagation of a wave along the surface of a vertically-stratified medium, bearing in mind that sometimes the refracting boundary is located somewhat deeper than its geometric surface.

If the vertical layers have different elastic properties, the wave corresponding to the surface of these layers is essentially not one wave but a group of waves with different dynamic features/11/. When a wave gliding along the surface of a vertically-stratified medium passes from layer b (Fig. 2) to layer a, one notes the recordings obtained by surface observations certain or even all the symptoms of interchanges of waves. Some of the waves corresponding to different vertical layers as will be shown below successfully replace each other along the line of observation, and some are registered simultaneously and interfere with each other usually over relatively short intervals of the profile.

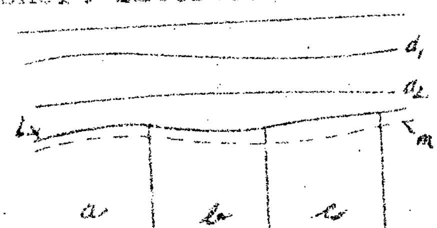


Fig. 62. Structure of a vertically-stratified layer. ℓ -- surface of vertical layers, m -- refracting boundary located somewhat deeper than the surface ℓ.

In those cases when the vertically-stratified medium is characterized by velocities thatare considerably greater tha the velocity in the covering rocks, the wave corresponding to the surface of this medium can be registered over definite distances from the point of explosion as a first wave. In the region of subsequent waves there may be registered, in addition to the waves corresponding to the separation boundary and the covering medium, also waves connected with the phenomena of reflection and refraction by different vertical separation boundaries.

When the vertically-stratified medium is not too deeply located, the waves corresponding to the separation in the covering medim are attenuated relatively rapidly with distance, and at certain distances from the point of explosion the recordings will display only the wave corresponding to the surface of the vertical layers. This distinguishes the records obtained in the case of vertically-stratified media from

the records obtained in the case of horizontally-stratified media, on which several waves are usually registered in one and the same interval of the profile.

We examine below certain principal features of the recordings, observed in the case of a vertically-stratified medium. In the examination it is assumed that the profiles are located across the direction of the vertical layers (Chapter III, Section 5).

Singularities of the Correlation of Waves in Observations on Longitudinal Profiles. Fig. 63 shows the scheme of the rays in the case of a vertical separation boundary between layers with different velocities. From an examination of this scheme, it is seen that in that case when the explosion point EP1 is located on the same side of the contact line as the layer with the lower velocity V_2, there exists simultaneously on the interval CD of the profile two refracted waves P_{121} and P_{1231}, and when the explosion point EP_2 is located on the same side of the line of the contact as the layer with the larger velocity V_3, the regions of registration of refracted waves P_{131} and P_{1321} are separated on the plane of observation. In section KL of the line of observation, the refracted-diffracted wave P_{131}' is registered as the first wave (the prime sign here and henceforth indicates in what portion of the path the wave is diffracted). In this connection, as the lines of contact intersect, the recordings on opposite systems differ from each other. These singularities of the waves registered in the intersection of the line of contact are independent of whether the points of explosinn are located directly over the contacting layers (Fig. 63, EP1) or whether the investigated medium contains other vertical separation boundaries and explosion points located above the layers, characterized by other velocities)EP3).

a) Explosion Point Located on the Side of the Layer with the Smaller Velocity. In this case, the in-phase axis of the waves P_{121} and P_{1231} intersect the certain point P of the section CD, and in the interval MD the P_{121} wave is registered after the P_{1231} wave. Thus, the simple wave P_{121} is replaced by an interference wave which in turn is replaced by the simple wave P_{1231}. The region of simultaneous existence of the waves P_{121}, P_{1231} at small depths of the vertically-stratified medium and sharp differences in the velocities in this medium and in the medium that covers it usually extends over a small distance, and both waves interfere with each other over the entire section CD (Fig. 63).

An example of the extent of the region of simultaneous existence of the waves P_{121} and P_{1231} is shown in Table 6.

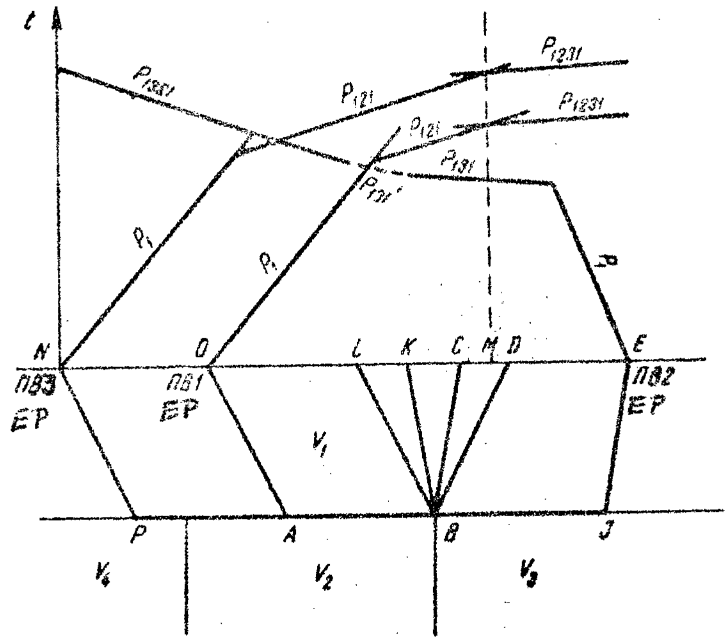


Fig. 63. Diagram of the course of seismic rays and theoretical hodographs in the case of a vertical separation boundary between layers of different velocities.

Table 6

H in meters	V_1	V_2	V_3	Extent of the Section CD, Meters
	In Meters per Second			
300	1500	3000	5000	78

In the region where the wave P_{121} is replaced by an interference wave and where this wave is replaced by the P_{1231} wave, one observes considerable changes in the form and amplitude of the recording. These features usually make it possible to exhibit reliably the interchange of waves.

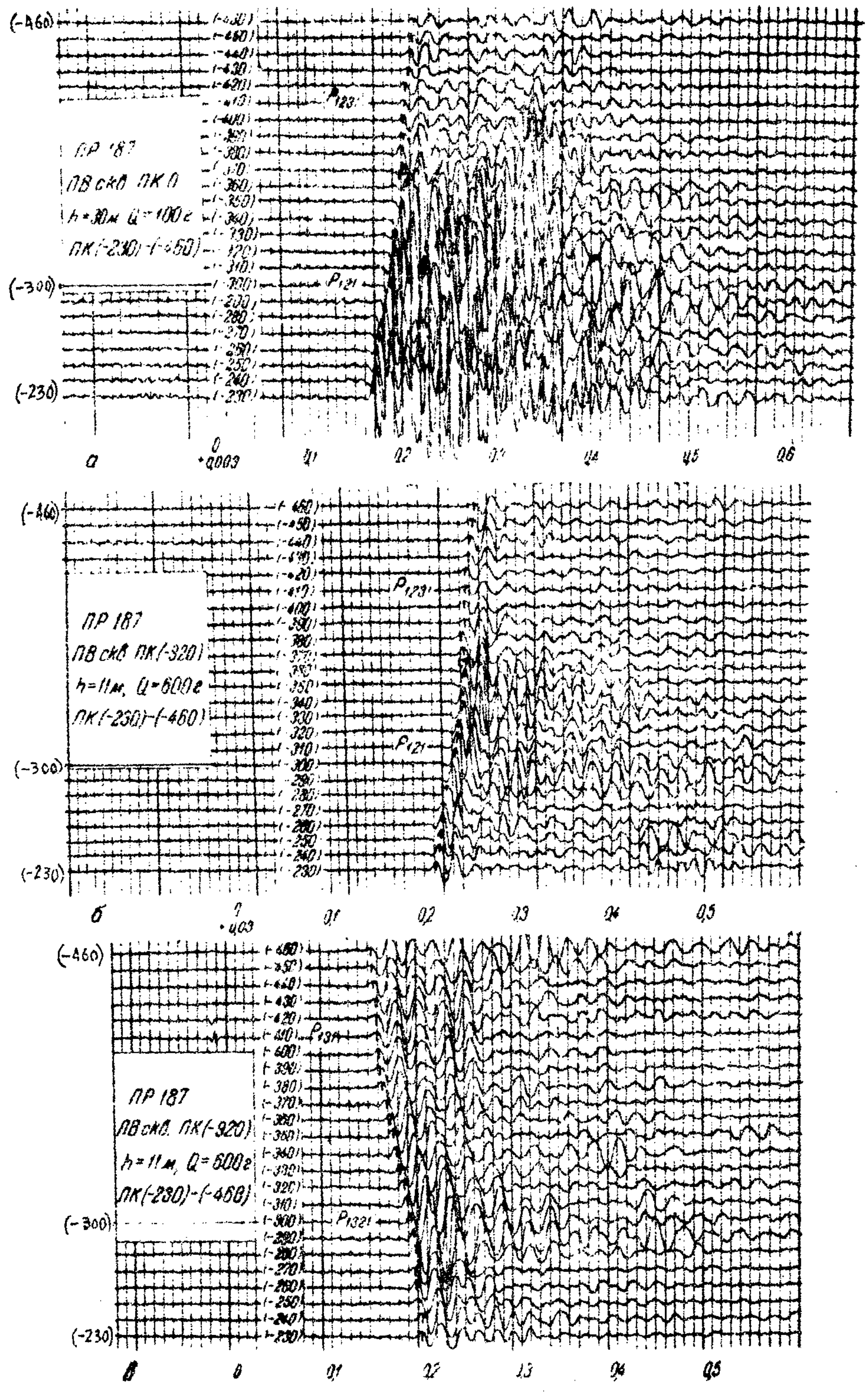


Fig. 64. Seismograms that illustrate the interchange of waves on a longitudinal profile upon intersection of the contact line. a -- interchange of waves as accompanied by interference phenomena; b -- there are no interference phenomena.

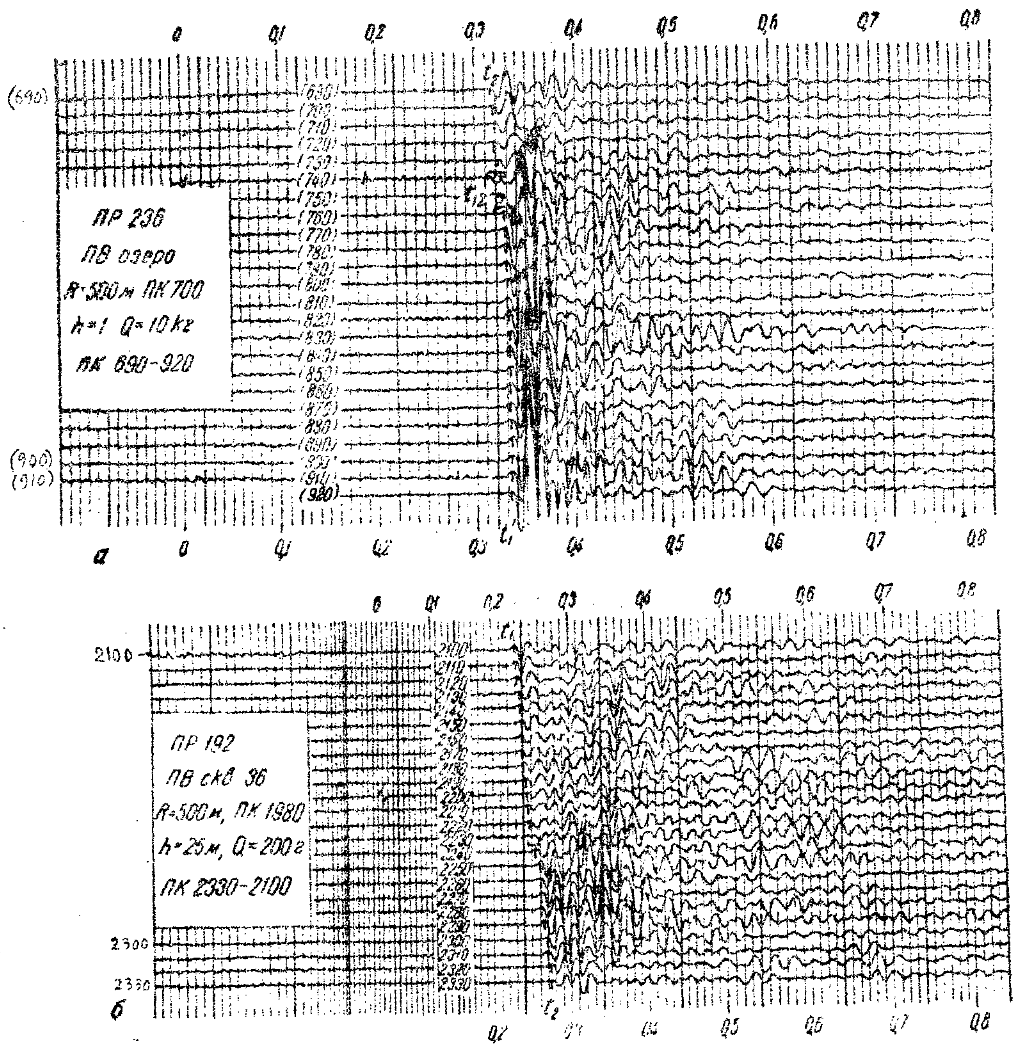


Fig. 65. Seismograms that illustrate interchange of waves on transverse profiles upon intersection of the contact line.
a -- interchange of waves as accompanied by interference phenomena;
b -- there are no interference phenomena.

On records obtained in the case of overtaking systems, the same waves will be registered, and the interchange of waves will be observed in the same station. The changes in the amplitude of the recording in intersection of the line of contact will be qualitatively similar, but certain quantitative differences may be observed, due to the fact that the changes in the amplitudes upon interchange of waves occur against a background of a smooth reductinn in the amplitude due to the increase in the distance from the point of explosion, and at different distances from the point of explosion to the line of contact this background is different.

b) Point of Explosion Located on the Side of the Layer with a Larger Velocity. In this case, the zone of interference of the refracted waves, corresponding to both layers, in the region where their in-phase axes intersect, are missing. In some cases, the refraction of waves P_{131} and P_{1321} differ considerably in shape and intensity of the recording, and the presence of a wave interchange may be established from these dynamic symptoms.

However, as shown by experience, in most cases it is possible to separate the interchanges of waves reliably on the recordings, obtained principally when the point of explosion is located on the side of the layer with the lower velocity. In these cases, the indicator of the interchange of waves, in addition to the dynamic features of the waves, are the interference phenomena -- the intersection of the in-phase axis of the refracted waves, i.e., the first criterion for the detection of a wave interchange (Section 1). By way of an example, Fig. 61 shows records obtained on a profile which intersects the contact line of two vertical layers, with overtaking and opposing systems of observations. On the overtaking systems (Fig. 64a, b) the interchange of the waves is clearly demonstrated by the sharp decrease in the amplitude which is observed in one and the same station. On the opposing system (Fig. 64c), the interchange of waves is manifested only in the variation of the apparent velocity and in the weak increase of the amplitude: an accurate position of the place where the interchange occurs cannot be clearly obtained. In this case, the increase in the amplitude connected with the interchange of the waves is masked by a smooth decrease in the amplitude due to the increased distance from the point of explosion.

Singularities of Correlation of Waves in Observations on Transverse Profiles. On the recordings obtained on transverse profiles, the difference in the shape of the recording and principally in the amplitudes of the waves corresponding to vertical layers with different elastic properties can be seen particularly clearly.

This is due to thefact that the distances from the point of explosion to the different points of the profile

differ little from each other. The zones of intersection of the in-phase axis of the waves (Fig. 65a), corresponding to different media, are possible for a similar location of the point of explosion, as indicated for longitudinal profiles. However, owing to the fact that on the transverse profiles the dynamic features of the waves are more clearly pronounced than on the longitudinal ones, wave interchanges can be located on the recordings in those cases, when the zones of the intersection of the in-phase axis are missing (Fig. 65b).

It should be noted that in some cases, based on the indicating dynamic features of the recordings, it becomes possible to disclose the contact lines of the vertical layers which differ considerably little in magnitudes of the boundary velocities.

8. Features of Correlation of Waves in the Case of Inclined Separation Boundaries and Angular Discrepancies Between Layers

Character of Seismograms. In the case of medium with inclined separation boundaries, characterized by different velocities, one can usually separate several waves on the recordings. Sometimes, the number of waves is relatively large.

In certain cases, usually at sufficiently large angles of inclination of layers or at very sharp differences in the velocities in the covering medium and in the refracting layer, the seismogram displays not only the waves that characterize the positive apparent velocities, but sometimes also waves with negative apparent velocities.

On the Location of the Zones of Interference and Wave Interchanges. In the case of inclined separation boundaries -- consolidated or not consolidated -- the interchanges of the same waves, unlike the case of the horizontally-stratified media, are located at different distances from the different explosion points, and unlike the vertically-stratified medium, they are located at different stations of the profile. This makes it difficult to disclose and identify wave interchanges in the recordings obtained at different points of explosion, compared with the cases of horizontally-stratified or vertically-stratified media.

Identification of Waves. The identification of waves by their dynamic features is sometimes difficult, for considerable angles of inclination, $\varphi > 5^{\circ}$, or at smaller angles of inclination but in the presence of angular discrepancies between the layers, the character of the recording may change substantially upon changing orientation of the profile or upon

changing position of the point of explosion. In particular, when the profile is located along the dropping refracting boundary, a strong attenuation of the refracted wave with increasing distance from the point of explosion is possible, whereas when the profile is located along the rise in the refracting boundary, the attenuation of the oscillations is weaker with distance; in some cases, the amplitude of the registered wave may increase with distance. In this connection, difficulties arise in identification of the waves registered at different points of explosion directly by the dynamic features of the recordings. Therefore, in the case of media with inclined separation boundaries, a thorough correlation of the waves by means of mutual points is of particularly great significance.

Disclosure of Angular Discrepancies in the Correlation of Seismograms, Obtained in Different Systems of Observation. In the correlation of seismograms the angular discrepancies can be displayed much more brightly on the recordings obtained with transverse profiles than on recordings obtained with longitudinal profiles. In the case of longitudinal profiles, the angular discrepancies, particularly at small angles of inclinations, may be displayed frequently only as a result of a quantitative interpretation, whereas in the case of transverse profiles the presence of angular discrepancies can practically always be disclosed directly on the seismograms. The divergent in-phase axes of refracted waves, corresponding to different separation boundaries, or differences in the time interval Δt between these waves at identical distances from the point of explosion, are both reliable indicators of the existence of angular discrepancies even at small angles between the refracting separation boundaries, on the order of 2-3 degrees (Fig. 44, waves t_2 and t_3). The kinematic features of angular discrepancies are frequently accompanied by clearly pronounced dynamic features, particularly in substantial differences in the variations of the amplitude of different waves along the lines of the transverse profile.

9. On the Correlation of Waves in the Case of Tepering Layers

In the case of tapering layers the records of refracted waves have dynamic and kinematic singularities which are described in detail in reference /35/.

These singularities are different depending on whether the point of explosion is located above the tapering layer or in that region where there is no such layer: we shall therefore consider them separately.

Singularities of Records Obtained with the Point of Explosion Located Above the Layer. The principal peculiarities of these recordings are as follows:

1) In the section where the thickness of the refracting layer decreases, the refracted waves corresponding to that layer is sharply attenuated with distance (Fig. 55b, wave t_4).

2) On seismograms there is registered a wave which is formed as a result of diffraction of the wave propagating in the refracting layer from the edge of this layer (Fig. 66, trajectories OABC, OABD, etc.). We denote these waves by P_{121}', where the prime, as in Section 7, denotes the portion of the path in which the wave is diffracted.

3) In certain cases, waves of complex type are registered. These waves, in the last part of the path, represent refracted waves, corresponding to one of the separation boundaries in that part of the medium where the tapering layer is already missing. The waves under consideration are formed in the following manner: the refracted-diffracted wave P_{121}', which falls at the limiting angle i_{13} (Fig. 66, trajectory OABK) on the boundary of layer 3, causes in medium 1 a front of refracted wave, propagating along the trajectories LM, NP, etc. Consequently, the production of these diffracted-refracted waves is connected with refracting at the limiting angle not by one refracting boundary, as in the case of ordinary refracted waves, but by two refracting boundaries.

We denote these waves by $P_{121'31}$. The interchange of the refracted waves P_{121}, by the refracted-diffracted waves P_{121}, is for the most part seen clearly on the seismograms (Fig. 67a). In correlation, in order to determine the place where the interchange takes place, one can usually use the following four criteria for recognition of wave interchanges:

1) the diffracted waves P_{121}' differ from the refracted waves P_{121} in the shape of the recording; the predominating frequency of the P_{121}' waves is sometimes considerably lower than that of the P_{121} wave;

2) the diffracted waves have a lower amplitude than refracted ones, and in some cases in going over from the refracted wave to the diffracted wave one observes a jump-like reduction in the amplitude;

3) the diffracted waves are more strongly attenuated with distance than the refracted ones, and furthermore owing to the sharp attenuation it is possible to trace them only over short profile intervals;

4) the diffracted waves are characterized by a curvilinear in-phase axis; the hodographs constructed on their bases have a hyperbolic form.

The replacement of diffracted waves of type $P_{121'}$ by complex waves of type $P_{121'31}$ is frequently not accompanied by noticeable changes in the form of the recording, and may be exhibited principally by the kinematic feature -- by the rapid change in the apparent velocity; a hodograph plotted on the basis of such recordings has an angle point in the region of the wave interchange (Fig. 66).

On seismograms obtained in the case of overtaking systems, the region of sharp attenuation with distance of the refracted wave P_{121} is fixed on one and the same interval of the profile. The changes in the dynamic singularities of the recording when the refracted wave P_{121} is replaced by the diffracted wave $P_{121'}$ is fixed on one and the same station of the profile. The changes in the apparent velocities, connected with the replacement of the wave $P_{121'}$ by the wave $P_{121'31}$, also occur at one and the same station. The overtaking hodographs of all the registered waves are parallel.

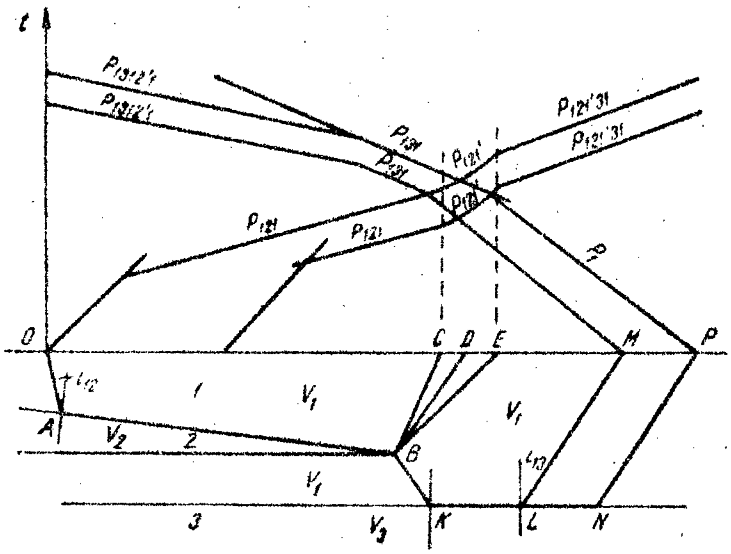


Fig. 66. Diagram of the course of seismic rays and theoretical hodographs for the case of a tapering layer.

<u>Singularities of Records Obtained with the Explosion Point Located in the Region Where There is no Layer.</u> In this case, as shown in reference /35/, waves of complex type may also occur; in particular, in some cases there are registered on the seismograms waves which are formed in the follow-

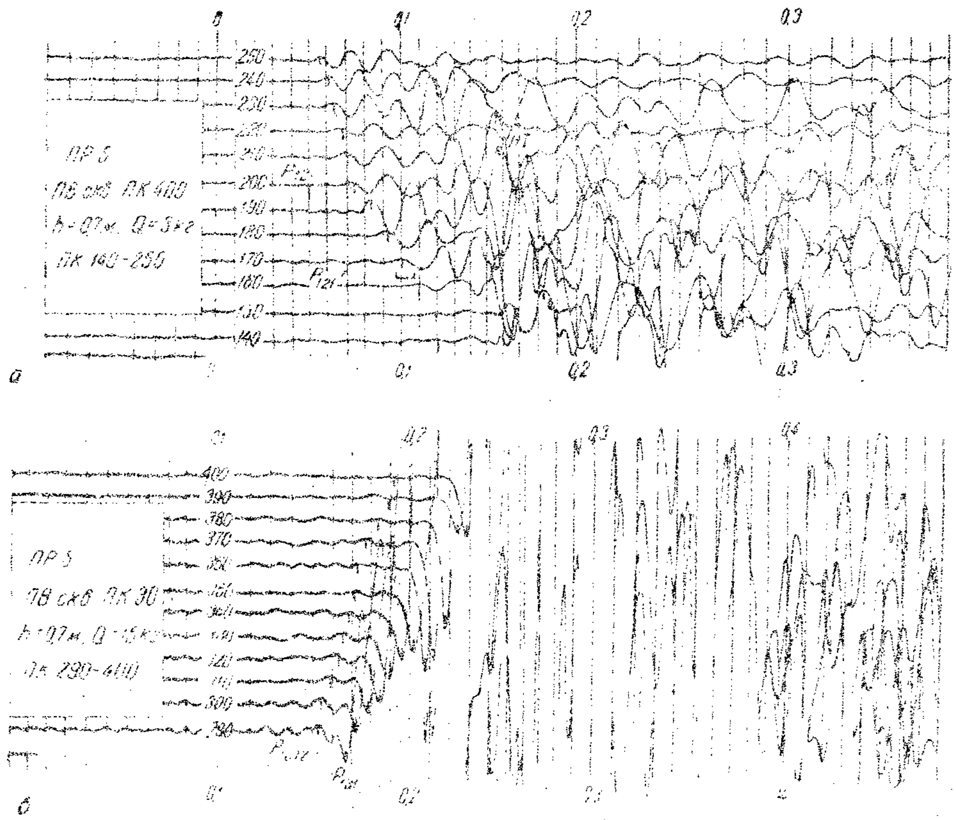


Fig. 67. Seismograms obtained in the case of a tapering layer.

ving manner: the refracted wave P_{131} (Fig. 66, trajectory 1H3), upon striking the edge of the tapering layer, produces a diffracted wave, which extends in this layer (trajectory AB). This wave carries with it a refracted wave in the covering medium (trajectory AO). We denote this wave by $P_{1312'1}$. The appearance of the complex wave $P_{1312'1}$, preceding the wave P_{131} is sometimes clearly seen on the recordings. The wave $P_{1312'1}$ is characterized by a considerably smaller amplitude, a different form of recording, and a different apparent velocity, than the wave P_{131} (Fig. 67b).

In the case of overtaking systems, the interchange of waves occurs in one and the same station, and the overtaking hodographs are parallel (Fig. 66).

From the kinematic point of view waves of different types are also possible, but until now they have not been observed. In particular, in the position of the point of explosion as considered above, all waves with hyperbolic in-phase axes, connected with the diffraction of the refracted wave from the edge of the layer, have been observed: when

the point of explosion is located over a tapering layer, these waves are clearly seen on the records.

<u>On the Possibility of Separating on the Recordings the Diffracted Waves of Type P_{121}'; $P_{121}'_{31}$, and $P_{1312}'_{1}$.</u> These waves, the occurrence of which is connected with diffraction phenomena, have low intensity compared with ordinary refracted waves. In those cases, when these waves are registered as first waves, experience has shown that they can be relatively simply separated on the recordings. This is possible in particular if the tapering layer has an increased velocity compared with the superior and inferior layers. If according to seismogeological conditions the waves P_{121}', $P_{121}'_{31}$, and $P_{1312}'_{1}$ should be registered in the region of succeeding arrivals, then in most cases they cannot be separated on the recordings against the background of other more intense waves.

10. On the Correlation of Waves in the Case of a Fault

Recordings of refracted waves in the presence of faults are distinguished for very pronounced dynamic peculiarities: some of these are analogous to the peculiarities observed in the case of tapering layers. The character of the recording in the case of crossing of the fault line is quite different, depending on whether the point of explosion is located along the ascending or descending portion of the fault; we shall therefore consider them separately.

In the analysis it is assumed that the profile line (longitudinal or transverse) is located approximately across the direction of extent of the fault line (Chapter III, Section 5).

<u>Singularities of Recordings Produced with the Explosion Point Located Above the Raised Branch of the Fault.</u> The experimental data have shown that when the fault line is crossed, the seismograms display clear wave interchanges with sharply pronounced changes in the form and intensity of the recording and sharp jumps in the times of arrival and variations of apparent velocities. In these cases, the interchange of waves can usually be readily separated on the recordings, since combinations of several criteria exist for the detection of the interchange.

At this position of the point of explosion, it is usually possible to separate on the recordings three principal waves: 1) a refracted wave P_{121}, corresponding to the raised wing (trajectories up to OCDE, OCAI, Fig. 68, a, b); 2) a refracted-diffracted wave P_{121}' which is formed as a result of the diffraction of the wave gliding along the raised

portion of the refracted boundary from the line of fault (trajectories OCAF, OCAK, etc.); 3) a refracted wave P_{dr} --, corresponding to the dropped branch.

The production of the refracted wave P_{dr} corresponding to the dropped branch is apparently connected with diffraction phenomena. Different schemes of production of these waves are possible. The most probable scheme may be described by the trajectory OHBMN (Fig. 68a, b). In this case, diffraction takes place of the passing refracted wave (trajectory HB) from the edge B of the dropped branch. The wave P_{dr}, corresponding to the dropped wing, must be denoted in this case by $P_{12\bar{2}'1}$; the bar over the number 2 denotes that the wave propagates along the dropped portion of the refracting boundary, whereas in general the velocities V_2, and $V_{\bar{2}}$ may be different.

Another possible scheme of production of the wave P_{dr} can be described by the trajectory OCAPMN (Fig. 68c,d). In this case, the wave diffracted from the edge A falls on the dropped branch of the separation boundary at a definite angle and gives rise to the refracted wave $P_{121'21}$.

Other schemes of production of the wave P_{dr}, corresponding to the dropped wing, are also possible.

The dynamic singularities of the refracted wave P_{dr} corresponding to the dropped branch, may sometimes differ substantially from the dynamic singularities of the wave P_{121}, corresponding to the raised branch. This may be due to changes in the lithological composition of the rocks, and also to the different degree of their destruction.

In overtaken systems, the foregoing kinematic and dynamic singularities of the recordings are observed on the same stations (Figs. 69b, c). The overtaking hodographs of waves are in this case practically parallel.

On transverse profiles, when the point of explosion is located over the raised branch, one observes the same singularities in the recordings, as in longitudinal profiles (Fig. 70).

<u>Singularities of the Recordings Obtained with the Point of Explosion Located Over the Dropped Branch.</u> In this case, two principal waves are separated on the recordings:

1) the refracted wave $P_{1\bar{2}1}$, corresponding to the dropped wing, and,

2) the refracted wave P_{ris}, corresponding to the rising wing.

The wave diffracted from the line of the fault, as shown by experience, cannot be separated in this case on the recordings. The jump in the times of arrival of the refracted waves, corresponding to the raised and the dropped wing, which is clearly observed when the point of explosion is located

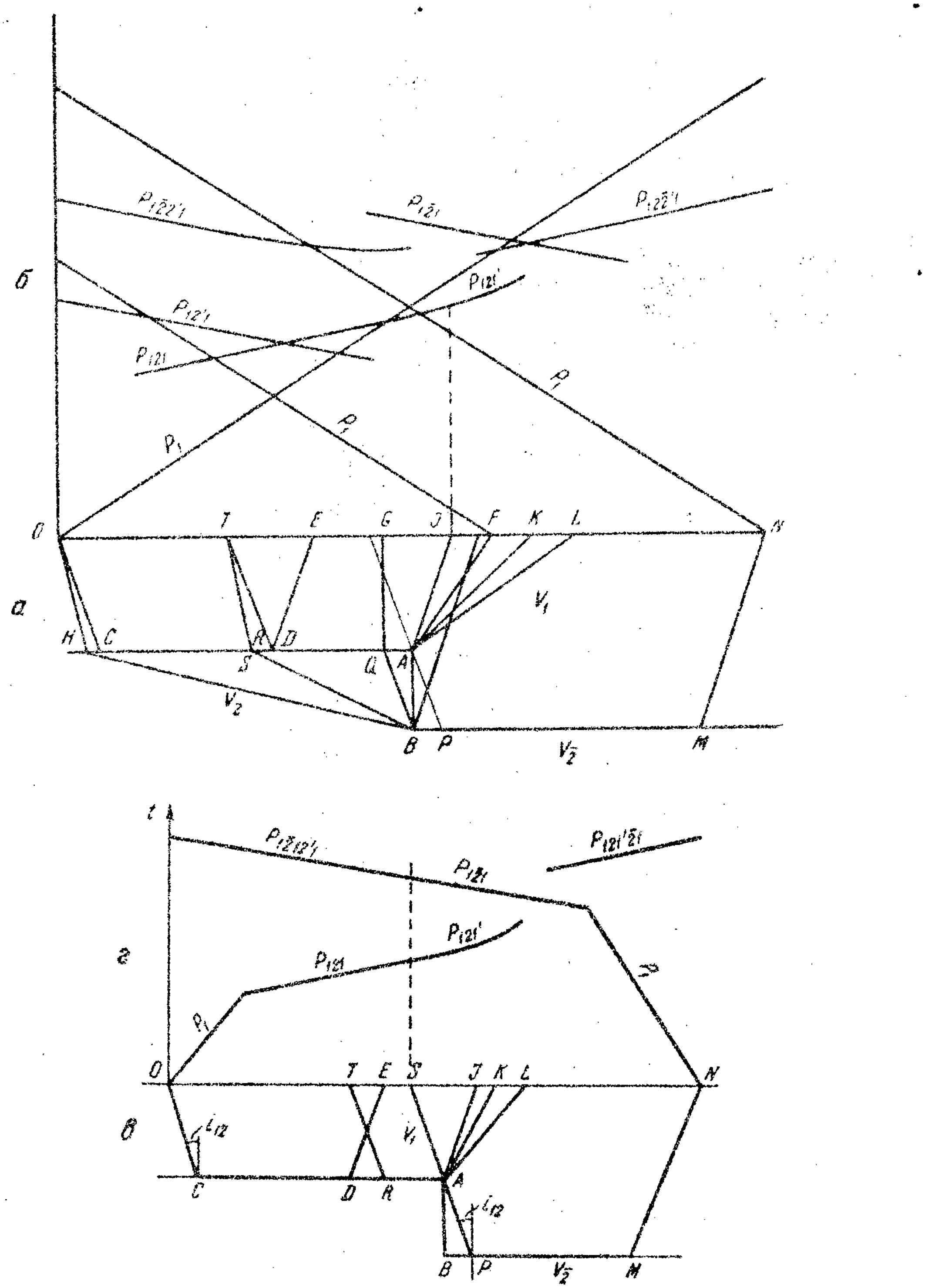


Fig. 68. Scheme showing the course of the seismic rays and theoretical hodographs in the case of a fault. a, b -- diffraction from the edge B; c, d -- diffraction from the edge A

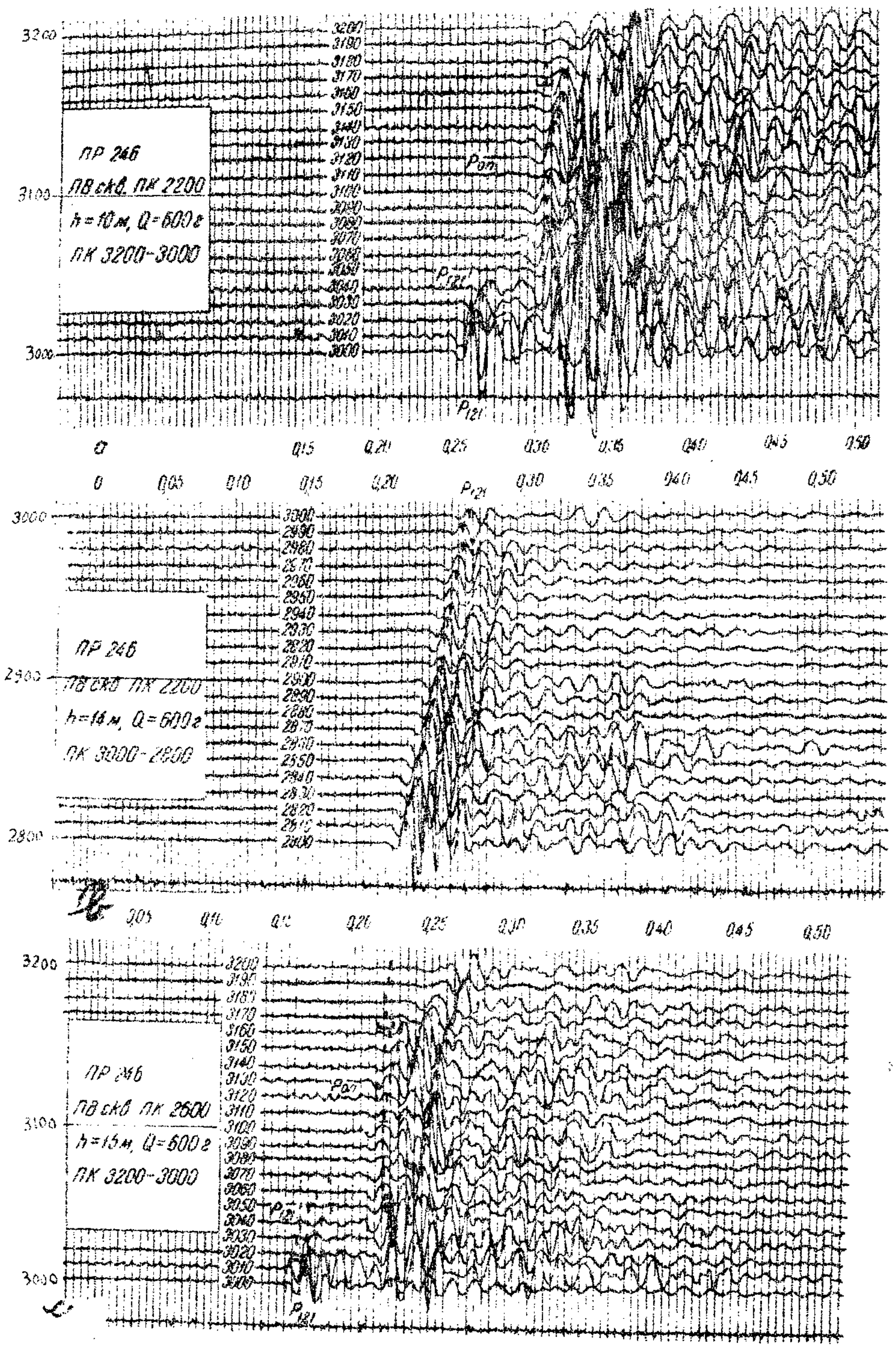


Fig. 69. Seismograms obtained on a longitudinal profile when the fault line is crossed. a, b, c -- seismograms obtained at the point of explosion located over the raised branch: a, b -- seismograms obtained on two neighboring stations: c -- seismograms obtained in the overtaking system of observations: d, e -- seismograms obtained in the opposite system of observations (point of explosion over the dropped branch).

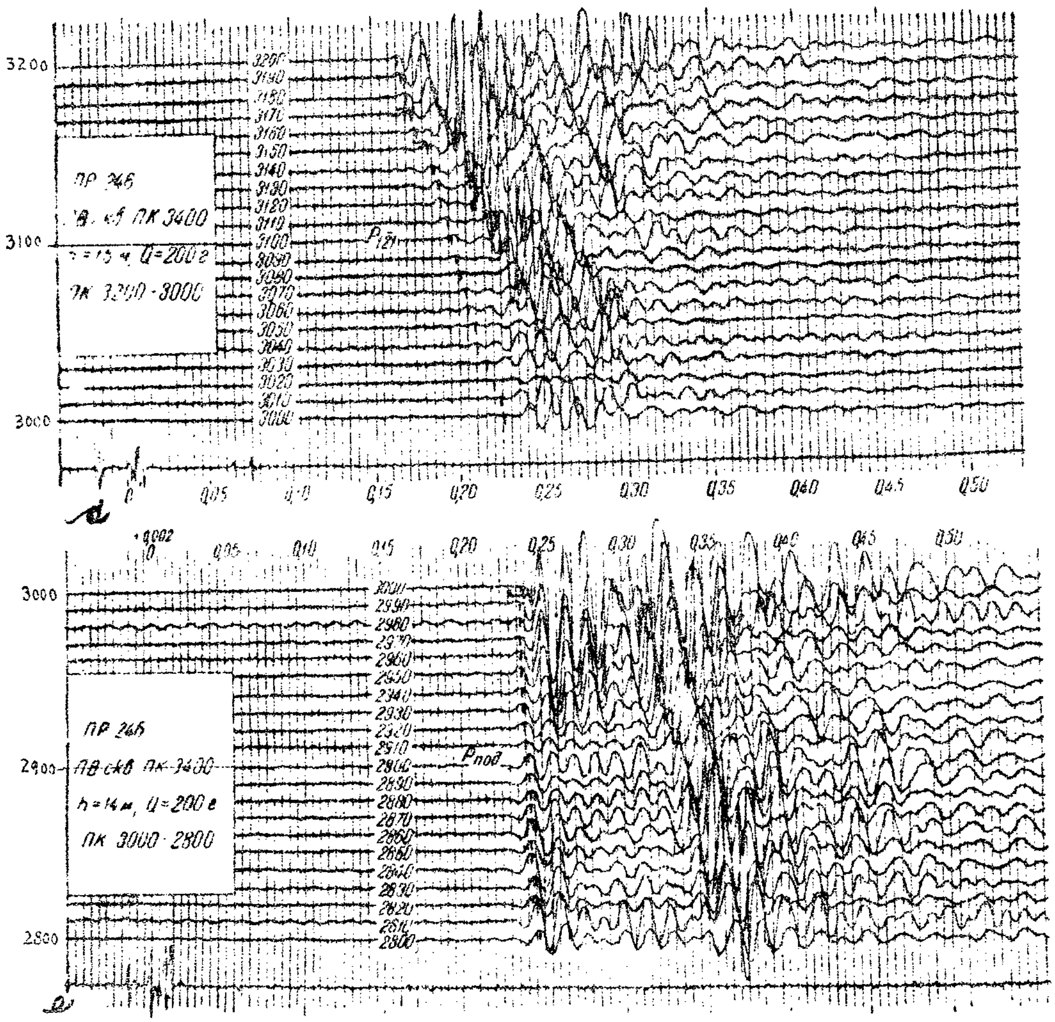


Fig. 69. (continuation of seismograms pertaining to Figure 69).

over the raised branch, is in this case either small or missing (Fig. 68b, d and 69d, e). The interchange of the refracted waves, corresponding to the raised and the dropped branches, is usually clearly separated on the recordings from the change in the dynamic singularities of the waves and from the sharp change in the apparent velocity. The production of refracted waves P_{ris}, corresponding to the raised branch, is apparently connected in this case with the diffraction phenomena, the same as the production of waves corresponding to the dropped branch whenever the point of explosion is located over the raised branch.

In the case of a point of explosion which is

comparatively far from the line of fault, different schemes of production of the waves P_{ris} are possible, for example, the trajectory NMBHO (wave $P_{12\bar{2}'1}$, Fig. 68a) or NMPACO (wave $P_{12\bar{1}'1}$, Fig. 68c). In the case of diffraction from the edge P (trajectory NMBH) the wave $P_{1\bar{2}2'1}$, corresponding to the raised wing, represents not a frontal refracted wave, but a transmitted refracted wave, produced as a result of the refraction of the wave which is diffracted from the edge B on the separation boundary.

Near the fault line, the apparent velocity of the wave may be close to infinite (Fig. 68a, b) owing to the refraction on the raised portion of the refracting boundary, and in some cases owing to refraction on the plane of the fault.

At a point of explosion F closer to the line of fault (Fig. 68a), the diffracted wave, propagating along the raised portion of the refracting boundary, can be produced when a straight wave is incident on the edge A of this boundary. The total trajectory of the rays is designated in this case on Fig. 68a by the letters FART, FACO; in this case, the wave P_{ris} is a wave of the type $P_{12'1}$.

In the case of propagation of the waves P_{ris}, in accordance with the scheme shown in Fig. 68c, d, the overtaken hodographs of the wave $P_{1\bar{2}12'1}$ and $P_{12'1}$ are always parallel.

In the propagation of the waves P_{ris} along the trajectories shown in Fig. 68a and b, the apparent velocities of the waves P_{ris}, registered in the overtaking systems, are practically the same, if the two points of explosions are located at a relatively long distance from the fault line, at which the waves $P_{122'1}$ can be formed. If one of the points of explosion is located close to the fault line and if there occurs in this point during the explosions a wave $P_{12'1}$, then the apparent velocity of the wave $P_{12'1}$ differs from the apparent velocity of the wave $P_{1\bar{2}2'1}$, registered with the overtaking system. In this connection, the overtaking hodographs, which are constructed on the basis of these waves, are also not parallel. Only at a large distance from the line of fault is there established a practical parallel orientation of the overtaking hodographs.

On Detection of Faults With the Aid of Records Obtained in Different Systems of Observation. The presence of a fault can be established reliably in that case, when the explosion point is located over its raised wing. The singularities of the recordings, obtained when the point of explosion is located over its raised wing. The singularities of the recordings obtained when the point of explosion is located over the dropped wing, in particular the absence of a jump in the time of arrival of the refracted waves, corresponding to the two wings of the fault, make it difficult to detect faults with

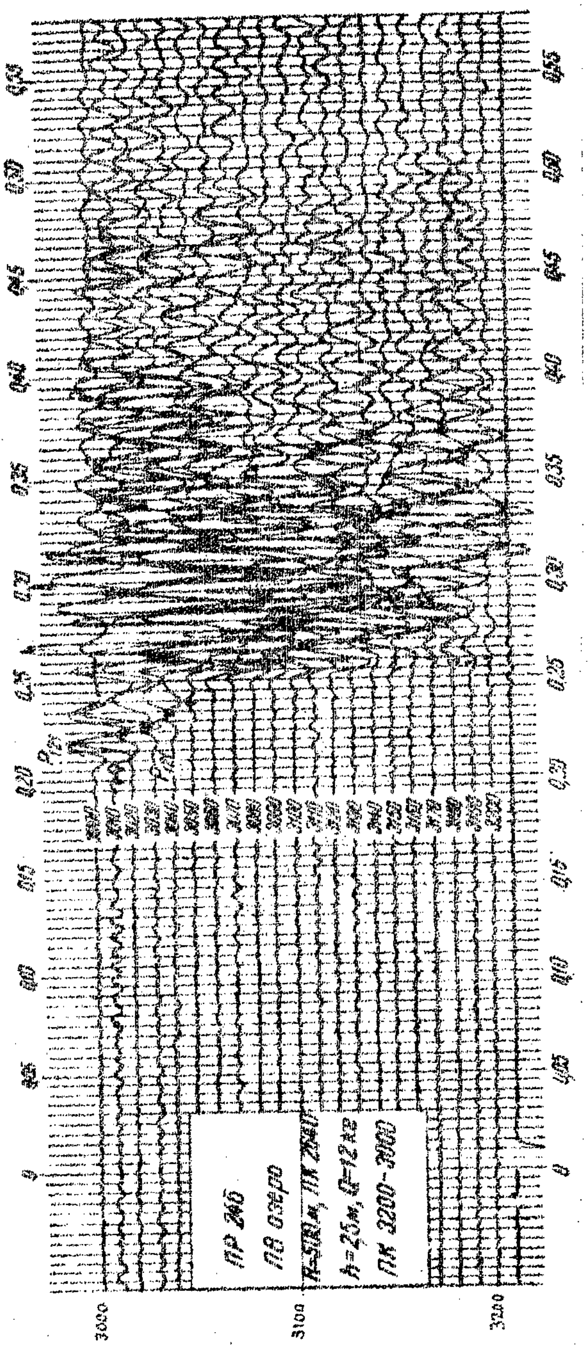


Fig. 70. Seismogram obtained on the transverse profile upon intersection of the fault line (point of explosion located over the raised branch).

the foregoing placement of the points of explosion. In these cases, in the case of longitudinal profiling, if there are no opposite systems, and particularly in transverse profiling, when the shooting is carried out with one explosion point, the fact of the existence of the fault may go undiscovered. On longitudinal profiles a certain indication of the existence of a fault may be the frequently observed non-parallel overtaking hodographs. However, this criterion is insufficient because non-parallel overtaking hodographs may be due also to other causes, particularly to the production of waves in the underlying medium.

It must also be noted that in the fault zone in any placement of the point of explosion, one sometime observed rapidly alternating waves, which can be traced over short intervals of the profile. These waves may be connected with reflection or refraction of different waves on the fault surface and serve as an indirect identification of the existence of a disturbed zone. However, for a reliable disclosure and tracing of a fault it is necessary to have opposite and overtaking systems or, at least, single systems under the condition that the point of explosion is located over the raised wing of the fault.

11. Technique of Correlation of Refracted Waves

1. Refracted waves corresponding to different separation boundaries must be marked on the records with different colors. The phase which is being traced must be noted by short dashes (see Fig. 41). In the correlation it is impossible to draw on the seismograms a single solid line, as is frequently done in the method of reflected waves, for in this case it is impossible to examine on the recordings all the detail of the form, which should be used in the correlation.

In the presence of a discontinuity in the correlation without an interchange in waves (for example, due to change in the surface conditions), it is necessary to note discontinuities, but it is not necessary to change the color in tracing the wave.

2. If it becomes necessary in tracing the wave to go over to a different phase, which can happen, in particular, in the case of strong attenuation of the oscillations, then it is necessary to trace on the common section of the profile both phases (Fig. 42) and this section should be sufficiently long, so as to be assured of the fact that the hodographs of the phases of one and the same wave are parallel. Different phases of the same wave must be marked with the same color.

3. Waves which have been traced at different points of explosion and corresponding to the same separation boundaries, should be noted on the recordings with the same color.

4. In the correlation, it is necessary to introduce the following symbols:

a) to note an interchange of one wave by another (Fig. 44);

b) to note a discontinuity in the correlation of the waves without the wave interchange (Fig. 49);

c) to separate the zones of sharp variation (attenuation or increase) in the amplitude (Fig. 46).

5. In the interference zones, in the absence of dominating waves, the phase of the traced complex interference wave must be noted with a fixed color, different from those colors which are used to denote each of the interfering waves in the region where they are separately traced.

In the presence of dominating waves, which can be traced through the zone of interference, without a discontinuity in the correlation, the phases of these waves must be noted with the same color as is used outside the interference zones.

CHAPTER V

INTERPRETATION OF THE LONGITUDINAL HODOGRAPHS OF REFRACTED WAVES

1. General Information

Observations of refracted waves along longitudinal profiles and interpretation of hodographs by these profiles make it possible to obtain, as a rule, the most reliable, quantitative information, which are amenable to the method of refractions (CMRW), regarding the section in a given region, namely: determine the depth and form of the refracting boundaries and find the velocities of propagation of seismic waves in the refracting layers.

The immediate purpose of a quantitative interpretation of longitudinal hodographs of refracted waves is the construction of seismic sections. On these sections, as in the method of reflected waves, one draws the seismic boundaries, but in addition to this data are also given, obtained by the method of refraction, on the velocities of the refracting layers. Information on the velocities in the layers yields a physical desctiption of the rocks and helps in geological interpretation of seismic observations.

Observations on longitudinal profiles and the results of their interpretation -- sections based on these profiles -- usually serve in the CMRW as a basis for other systems of observation: for non-longitudinal (transverse etc.) profiles, for networks of profiles with a single explosion point, etc.

Initial data. The initial data for the construction of sections on longitudinal profiles are as follows: 1) the observed hodographs of the phases and sometimes the entrances and phases of refracted waves (usually frontal refracted waves); 2) data on the strata or mean velocities in the covering layers; 3) additional information, necessary to calculate the depth of the explosion, the zones of small velocities (the weathering zones), and the topography.

Basic premises. In the interpretation of longitudinal hodographs of refracted waves it is usually assumed that the prospected medium is isotropic, but generally inhomogeneous and the problem can be considered as a plane problem, i.e., all the rays used for the construction lie in one and the same plane, to which the section belongs; this plane is the norm with respect to the boundary of the separation of the "plane of rays."

The layers of sedimentation and metamorphic rocks usually have more or less clearly pronounced stratified structure, which appears in the spatial distribution of the velocities of propagation of the elastic waves. At an approximately horizontal stratification, the velocities change with depth usually not monotonically, but alternately increase

and decrease; the general increase in the velocities with depth is usually observed only on the average [54]. In this connection, the following assumption is made regarding the velocity structure of the medium, and this is indeed used in the interpretation of hodographs of the refracted waves.

It is assumed [53] that the medium consists of regions of two kinds: more or less thick layers, characterized by layer velocities V and of layers which may be relatively thin, with increased boundary velocities V_b, and the existence of the latter is taken to be the cause of the existence of frontal refracted waves, to which the observed hodographs correspond.

The layer velocities V, in the case of an approximately horizontally-stratified distribution of the velocities in the medium, are the true velocities of propagation of seismic waves along the vertical, averaged over the depth. The law of variation of the layer of velocities with depth, $V = V(z)$, is usually represented either in the form of of a piecewise-constant function (graphically in the form of a staircase line) or else in the form of a continuous function (smooth curve, in the particular case of a linear law -- a straight line).

The values of the layer velocities V are assumed to be independent of the values of the boundary velocities V_b, inasmuch as the latter may characterize such thin layers, that their role in the averaging process used to determine V may be vanishingly small. The boundary velocities are always greater than the velocities in the covering rocks, and may be greater or at least equal to the velocities in the underlying layers. Only in the latter case do the hodographs of the frontal refracted waves permit a direct determination of the layer velocity (which in this case is equal to the boundary velocity). In general, however, they do not give a direct idea of the layer velocities.

The process of propagation of velocity of waves in such a medium, which includes thin layers with increased velocities V_b, is represented in the following form. In the medium as a whole, the waves propagate with layer velocities V approximately the same way as if there were no thin layers with velocities V_b. But upon meeting with a thin layer of increased velocity V_b, a straight wave incident at a critical angle i ($\sin i = V/V_b$) gives rise to a wave which glides along this layer with a velocity V_b. In turn, the gliding wave produces in the surrounding medium frontal refracted waves, the fronts of which are displaced in space again with thelayer velocities V.

Making this assumption, it is possible to interpret the hodographs of the refracted waves, corresponding to any particular defined boundary, in a certain sense, independently of the hodographs corresponding to other separation boundaries in the covering layer. In the interpretation of the aggregate of hodographs for each given boundary, we shall speak of a boundary velocity which characterizes only that particular boundary. On the other hand, the entire covering medium will be characterized by a law of distribution in it of only layer velocities, independent of whether there exists in it other thin layers with boundary velocities or not.

With respect to the velocities in the covering medium, the following particular assumptions can be made.

a) $\bar{V}$ = const -- assumption of a constant average velocity. The average velocity is calculated along the vertical from the surface of the soil to the given depth. In this case the velocity V in the entire medium, covering the considered boundary, is assumed to be constant and equal to the average velocity $\bar{V}$, which is determined to a certain depth, at which this boundary is located. Such an approximate assumption does not result in great errors, provided the depth H of the boundary and the corresponding velue of the velocity $\bar{V}$ change little along the investigated portion of the profile.

b) For different boundaries R_i one assumes different values $\bar{V} = \bar{V}_i$ in accordance with their average depths H_i (i 1, 2, 3, ...).

$\bar{V} = \bar{V}(z)$ or $\bar{V} = \bar{V}(x)$ -- assumption of a variable average velocity, it being assumed furthermore that the velocity $\bar{V}$ depends on the depth z or on the distance along the profile x. In this case it is assumed arbitrarily that the seismic rays, in spite of the inhomogeneity of the medium, remains straight (the method of "average velocities"). Such an approximate assumption does not lead to great errors, provided the rays do not make excessive angles with the axis, along which the velocity is measured. Most frequently the assumption of the variable velocity is used in the version $\bar{V} = \bar{V}(z)$, which usually leads to small errors, if the angles of inclination of the boundaries are small;

c) V_k = const -- assumption of constancy of the layer velocity in each of the layers k (k = 1, 2, 3, ...). Here account is taken of the refraction of the rays on the boundaries between the layers.

The boundaries between layers are sometimes assumed to be refracting boundaries in the covering medium, determined from other hodographs of refracted waves by means of constructions, analogous to those with which the position of the sought boundary is determined. The boundary velocities corresponding to these intermediate boundaries (more accurately, thin layers) can be either equal to or greater than the layer velocities in the underlying layers;

d) $V = V(z)$ -- layer velocity depends on the depth. The rays are assumed to be curved and the constructions are made in full correspondence with the laws of geometric seismics. For this purpose use is made of previously constructed ray diagrams, the same as in the method of reflected waves.

The choice of any of the foregoing assumptions is dictated essentially by the following circumstances: the character of the seismogeological section in the region where the work is performed (angles of inclination of the layers etc.) the degree of completeness and reliability of the initial data, the requirements regarding the accuracy of the results of the constructions, and also the time and forces available for the interpretation. In the case of tentative interpretation one usually uses the simpler assumptions, whereas in final interpretation more complicated assumptions are used, which take into account the real conditions with greater approximation.

Principal methods of interpretation. In working with CMRW the principal methods of interpretation of longitudinal hodographs are the following: a) the exact method of time fields for the construction of boundaries and determination of boundary velocities and b) approximate method: difference hodograph for the determination of boundary velocities, and the t_0 method (the variant of themethod of "arithmetic means") for the construction of the boundaries themselves.

The method of time fields makes it possible to carry out exact constructions, within the capabilities of geometric seismics, of the refracting boundaries of any form (in particular, with faults etc.), and to determine the boundary velocities. This method does not need the use of approximate representations of the "method of average velocities", where the average velocity $\bar{V}$ is assumed to be a quantity that is in general variable, usually depending on the depth, but at the same time it is assumed that the rays are straight lines which contradict the laws of geometric seismics.

In the processing of opposing hodographs, the method of time fields yields nearly equal results to those of the "conjugate points" method [14], in particular in the fact that it makes it possible to take into account the so-called "drift" of the points of the refracting boundaries relative to the points of observation on the profile. But it is more general and in practice more convenient than the method of conjugate points", particularly in application to multiple-layered media.

The method of time fields makes it possible to process also single hodographs. In this case it replaces the "triangle method" [14], and in addition makes it possible to carry out the constructions in practice more accurately, without acc umulation or with lesser accumulation of errors along the profile, and in addition it is applicable for both constant and variable velocities. Furthermore, it makes it possible to take into account not only the waves that glide along the separation boundary, but also the waves that penetrate inside the underlying layer (i.e., it permits taking the "penetration" phenomenon into account).

Finally, this method makes it possible to determine the boundary velocities V_b with both opposing and overtaking hodographs of refracted waves, for any number of layers and for any form of refracting boundaries, and furthermore for both constant and variable velocities in the layers.

The difference-hodograph and t_0 methods are based on the use of non-rigorous representation of the "method of average velocities": in the calculations it is assumed that the rays are straight, even though the velocity $\bar{V}$ may be variable. In view of this it becomes necessary to assume, in particular, that $\bar{V}$ does not vary too much in space. It is further assumed that in the plane of the rays the boundary differs little from a linear one and the phenomena of penetration are lacking. The so-called "seismic drift" -- the displacement of the horizontal projection of the point of emergence of rays from the refracting layer relative to the same point on the profile, where this ray is observed,

is taken into account in this method only partially; for example, in the interpretation of opposite hodographs one compares not the "conjugate" elements of the hodographs, but the boundaries that correspond to one and the same point, and the elements of the hodographs in one and the same point of the profile, which correspon to different points of the boundary. This makes it necessary to introduce the assumption that there is a weak variation of the boundary velocity V_b along the profile. Finally, in the determination of V_b one adds further the assumption that the angles φ of the inclination of the boundary are small (so that $\cos \varphi \approx 1$).

In spite of the foregoing non-rigorous assumptions and limitations, these approximate methods can be frequently used with great success. Usually the interpretation of longitudinal hodographs is carried out first by approximate methods, and it is then clarified to the extent to which the general character of the construction of the medium admits of their use. Next, in those places where the structure of the medium is found to be complicated, for example, where the boundaries are strongly curved or inclined at considerable angles and where the velocities V_b change sharply, the results of the approximate constructions are controlled and refined by employing the method of the time fields. The latter is used also where it is necessary absolutely to take into account the seismic drifts, and also where it is necessary to take special account of the ffects of refraction of waves by the intermediate boundaries in a very inhomogeneous covering medium.

In the CNRW it is possible to use also additional auxiliary methods of interpretation of hodographs of refracted waves (see, for example, [14, 58]).

The section constructed along the longitudinal profile is conditionally referred to the "ray plane", which is normal to the refracting boundaries. If the angles of the lateral inclination of the boundaries, i.e., the inclination in the planes perpendicular to the direction of the longitudinal profile, are small (for example on the order up to 10°), then the section can usually be conditionally referred to the vertical plane, in which the longitudinal profile lies. At large angles of lateral inclination, this becomes unacceptable, and this must be taken into account in particular in the compilation of structural maps.

2. Preliminary Operations with the Hodographs

As a result of the correlation of the phases of oscillations one first plots from the seismograms the hodographs of the phase of the waves -- simple and complex. The most important problem in the interpretation of seismic observations, preceding the construction of the sections, is the recognition of the waves -- the separation of the simple waves from the other oscillations, the establishment of the mutual relationships and correspondence to definite boundaries of separation in the medium. The recognition of the waves is carried out to a great extent in the analysis of the seismograms, but it is continued in the compilation of the hodographs.

On the basis of the phase hodographs of the simple waves one constructs hodographs of the entries of these waves. This is done by introducing into the phase hodographs definite corrections. Other corrections are introduced to take into account differences in the conditions, under which the observations have been carried out, from those simpler conditions, which are assumed in order to carry out the quantitative interpretation of the hodographs -- the construction of the sections: for example, it will be assumed that the points of explosions are located on the surface of the earth, that there is no zone of small velocities, etc.

It is then necessary to interrelate accurately the systems of hodographs, corresponding to one and the same boundary, by means of mutual points, to construct summary hodographs of the refracted waves, and to construct the lines $t_0(x)$. The corrected interrelated summary hodographs do serve as the basis for the construction of the sections.

Corrections. It is possible to introduce the following corrections: 1) for the phase, i.e., for the difference in the time of arrival of the traced phase of the simple wave and the time of arrival of the front of this wave; 2) for the horizontal displacement of the point of explosion from the line of longitudinal profile; 3) for the depth of explosion; 4) for the topography.

The correction for the phase is introduced by starting out with the assumption that the hodographs of the phases and the hodograph of the entry (front) of a given wave are parallel to each other, i.e., that for a given phase the value of the correction is constant. The value of this correction can be readity established if on certain seismograms the considered refracted wave has also clear cut first arrivals and a clear cut phase. The clear cut arrivals and the phase can sometimes be obtained at one and the same point and on different tapes at different intensities of oscillations. The values of the correction thus obtained are used for a given wave on those portions of the profile, where it is traced only by phase. In those cases when the considered wave gives in no place any clear cut first arrivals and was traced only by phase, the magnitude of the correction for the phase is estimated approximately, as is done in the method of reflected waves.

The corrections for the horizontal displacement of the point of explosion from the line of the profile is introduced (if such a displacement exists) unlike the remaining corrections, not in the times of observation, but in the observation stations. The points of explosions are shifted along the profile perpendicularly to this line. During explosions at these points, the observation points are shifted along the line of profile in such a way, that the distance along the profile from the corrected transferred point of observation to the shifted point of explosion remains the same, as between the true point of explosion and the point of observation in the location (more accurately, in plan).

Corrections for the depth of the explosion and for the zone of small velocities (the weathering zone) is determined in exactly the same way as in the method of reflected waves (see, for example, [14, 58], and require no special explanation. The same pertains also to the topographic corrections. The latter can however be not introduced at all, but in its place it is necessary to construct the profile not from the reduced line, but from the line of topographical relief; in practice this is done most frequently.

We note that it is always necessary to introduce also certain other of the aforementioned corrections. Thus, if the given wave is observed by first arrivals, then, naturally, the correction for the phase drops out. It is unnecessary to introduce constant corrections in those hodographs of refracted waves, which will be combined into a single summary hodograph by means of parallel transfer, provided only the times by these hodographs will not be used to interrelate the system by mutual points.

The calculation of the corrections and their introduction become simpler also in that case when experience shows that under specific conditions, in a definite region of operation, the fluctuations in the magnitude of the particular correction or in the sum of certain corrections do not exceed the permissible error of time measurement by seismograms or by hodographs, which in turn corresponds to a known error in the determination of the depths of the refracting boundaries. Then the average value of such a correction or sum of corrections, determined beforehand, can be introduced in all the observations without a particular determination of the corrections in each individual case. Such, in particular, may be the case of corrections for the zone of small velocities, so that part of the work consumed in the shooting of the zone can be eliminated, and additional prospecting work can be performed instead.

Recognition of waves. At the stage of hodograph compilation, this recognition consists of determining more accurately to which waves, for example, refracted or reflected, corresponds any observed hodograph or portion of the hodographs, and also which waves and their hodographs corresponded to the same separation boundaries.

a) Recognition of refracted waves (distinction from reflected waves). Hodographs of refracted waves are distinguished from the hodographs of reflected waves primarily in their shapes; the separation boundaries are approximately plane and other simple conditions are satisfied, the hodographs of reflected waves are curved and close to hyperbolas, while those of refracted waves are almost straight lines. However, at these relatively large distances from the point of explosion, where there is a danger of assuming refracted waves to be reflected, or vice versa, in the region of initial points of hodographs of refracted waves and further -- the hodographs of reflected waves become also close to straight lines; therefore they cannot be distinguished directly from the hodographs of refracted waves by simple examination. This problem becomes easier if one compares hodographs obtained experimentally, with previously calculated theoretical hodographs, which

is most easily done with the aid of a template of theoretical hodographs of reflected waves [55].

Refracted waves connected with the same separation boundary, are usually characterized by a parallelness of the overtaking hodographs. The parallelness is observed if the rays of this wave glide along the refracting boundaries. But if they penetrate within the refracting layers, then as the distance to the point of explosion increases, the apparent velocities as determined by the hodographs increase. For reflected waves one observes the opposite: as the point of explosion becomes more distant, the apparent velocities as determined by the hodographs decrease.

In the recognition of refracted waves from reflected ones use is also made of the fact that the reflected waves usually are not observed at distances from the point of explosion, exceeding the distance to the initial points of the hodographs of the refracted waves, corresponding to the same boundaries (Chapter I, Section 2).

b) Identification of refracted waves corresponding to one and the same boundary. The principal criteria for the referral of refracted waves to one and the same boundary are the following: equality of the times as determined by the hodographs at the mutual points, and approximate parallelness of the overtaking hodographs.

A certain non-parallelness of the overtaking hodographs of the refracted waves may be due, in addition to the penetration effects, also to the curvature of the refracting boundaries in the space, when the seismic rays, arriving from different points of explosion, do not lie in the same plane.

In practice one frequently encounters cases when the effects of penetration and other causes, which cause deviations from the parallelness of the overtaking hodographs, can be neglected. The non-parallelness of overtaking hodographs can be reduced, by reducing the intervals between corresponding points of explosion.

In the comparison of refracted waves and their hodographs, obtained on one and the same longitudinal profile, but by systems of hodographs which do not have correlation, or else which are not intercorrelated with intersecting or separated longitudinal profiles, the criteria for the identification of waves or their dynamic singularities (Chapter IV), and also the falues of the times t_0 (see below), the depth and form of the boundaries by sections, and the values of the boundary velocities.

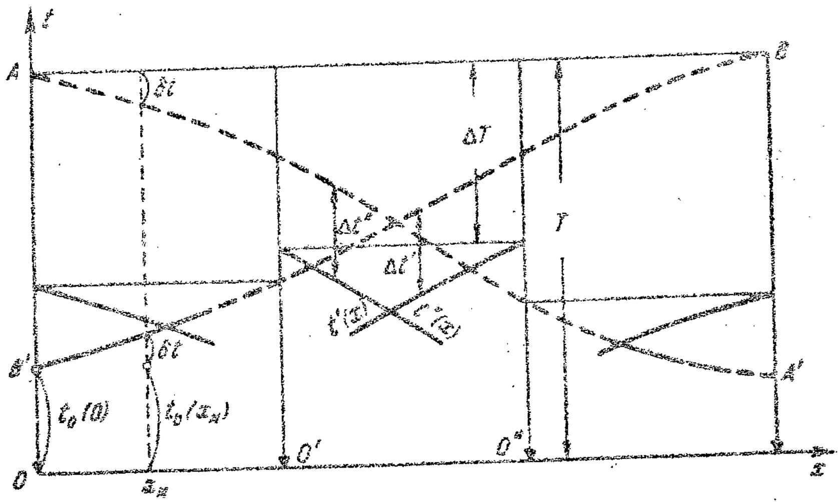


Fig. 71. Construction of summary hodographs and t_0 (x) lines.

Interrelation of systems of hodographs. Construction of summary hodographs and t_0 (x) lines. The method of construction of summary hodographs has been well known for a long time (see, for example, [14, 52]) and consists of transferring the overtaking hodographs, corresponding to one and the same boundary, parallel to the time axis in such a way, that they become continuations of each. Summary hodographs (lines B'B and AA' on Fig. 71) are constructed both for direct (B'B') and reverse (AA') hodographs. Summary opposing hodographs are interrelated by mutual points, as also are individual opposing hodographs. If the overtaking hodographs, connected into one summary hodograph, do not have overlaping sections and the magnitude of the parallel shift $\Delta t'$ (or $\Delta t''$) can be varied somewhat, than in shifting two opposite hodographs, which have mutual points (Fig. 71) it is necessary to observe the following rule: the sum of shifts $\Delta t'$ and $\Delta t''$ of opposite hodographs should be equal to the shift ΔT of the mutual points [52]. This rule can be derived from the reciprocity principle. If this rule is observed, the results of the construction of the refracting boundary by sections of hodographs before and after the shift would be identical to each other; in particular, the depth of the boundary constructed by shifted hodographs will be found to be exactly the same as in the construction of the boundary by unshifted hodographs.

The changeover from simple hodographs to summary ones for furthr processing is quite legitimate in that case, when there is no penetration of rays within the layers that underlie the boundary, to which the considered hodographs correspond. However, if the phenomena of penetration do exist, then they can be neglected in the case of small angles of incidence.

If opposite hodographs -- simple or summary -- have crossing sections, then it is possible to use these to plot the curves $t_0 = t_0(x)$, "times at the points of explosion". These curves join the points of intersection of the continuations of the hodographs of the refracted waves with the time axis, passing through the corresponding points of explosion.

The curves $t_0(x)$ can be determined from the points located not only "above" the points of explosion. The position of any point, with coordinates x, $t_0(x)$, located on the curve $t_0(x)$, is determined by the equation

$$t_0(x) = \vec{t}(x) + \overleftarrow{t}(x) - T, \tag{5}$$

or in a different form

$$t_0(x) = \vec{t}(x) - [T - \overleftarrow{t}(x)], \tag{6}$$

where $\vec{t}(x)$ and $\overleftarrow{t}(x)$ are the times determined from two opposite hodographs at the point x of the profile, and T is the time of arrival as determined by mutual points (Fig. 71).

In accordance with Eq. (6) the technique of constructing the points x, $t_0(x)$ is as follows [52]: one measures a section δt from one of the opposite hodographs along the line AB, joining the mutual points of the hodographs, and this section is laid off downward from the second hodograph. As a result, the sought point is obtained.

The curves $t_0(x)$ differ from the "arithmetic-mean" curves, which are used in the method bearing the same name [14], in that their position does not depend on the processed system of hodographs, i.e., in that it is very important that it be fully determined by the structure of the medium. With this, the structure of the medium may be of any kind: refracting boundary curved and velocities $\overline{V}$ and V_b variable; there should only be no penetration.

The curve $t_0(x)$ can be used for the calculation of the position of the refracting boundaries. However, their construction is best carried out also in those cases, when they are not used directly for this purpose. The determination of these curves does not require knowledge of the velocities of the covering medium, which is necessary for the construction of the sections. At the same time, the curves $t_0(x)$ make it possible to obtain a clear general idea of the behavior of the boundaries also before data are accumulated concerning these velocities. Furthermore, the curve $t_0(x)$ can help, as already mentioned, in recognition of waves corresponding to different boundaries,

and in the identification of waves pertaining to the same boundaries. This is particularly important when the correlation of the waves by seismograms is not fully reliable, for example, as a result of mutual interference between waves.

3. Determination of Velocities in the Covering Medium

Summary hodographs or, where they cannot be obtained, simple hodographs, and the $t_0(x)$ lines, make it possible to plot a section, provided the velocities in the medium covering the considered refracting boundary are known. Let us proceed to a discussion of methods of determining these velocities.

Average velocity $\bar{V}$. To determine the velocity characteristics of the medium covering any of the considered boundaries, in the correlation method of refracted waves, as in the method of reflected waves, one uses most frequently the idea of the "average velocity" $\bar{V}$. In the case of a horizontal stratified medium, when the tru velocities change only with depth z, the average velocity $\bar{V}$ is usually meant to be the average velocity of propagation of longitudinal waves along the vertical from the surface of the earth $(z = 0)$ to a given depth z.

In the present section we shall have in mind this meaning of the quantity V. This quantity is determined most accurately and directly with the aid of seismic coring. Indirect determinations of these quantities are possible by means of the hodographs of reflected ([55] and others) and refracted waves.

Finding the average velocities $\bar{V}$ and depths $z = H$ of refracting boundaries from times t_0 for a known law $\bar{V}(z)$. Let us assume that the average velocity $\bar{V}$ changes with depth in accordance with a known law $\bar{V} = \bar{V}(z)$ (the curve $\bar{V}(z)$ on Fig. 72). Let us see how to find with the aid of this graph that value of the average velocity $\bar{V}$, which is necessary for the interpretation of the observed hodographs of the refracted waves.

In the method of reflected waves the analogous problem is solved simply: the hodograph of reflected waves $t^{refl}(x)$ is used to find the "time at the explosion point" t_0^{refl} (Fig. 73), and then the sought value of $\bar{V}_H$ of the average velocity $\bar{V}$ is determined by using the graph $\bar{V}(t_0^{refl})$ on Fig. 72.

If in work with the CMRW one observes simultaneously with the refracted waves also the reflected waves (combined method), and if together with the considered hodograph of refracted wave $t(x)$ there is also obtained the corresponding hodograph of reflected wave $t^{refl}(x)$ corresponding to the same boundary R, then the problem of finding the value of $\bar{V}$ necessary for the interpretation of the hodograph of the refracted waves reduces to the following; the velocity $\bar{V}$ found by the hodograph of reflected waves is used also for the construction of the boundary based on the corresponding hodograph of the refracted waves.

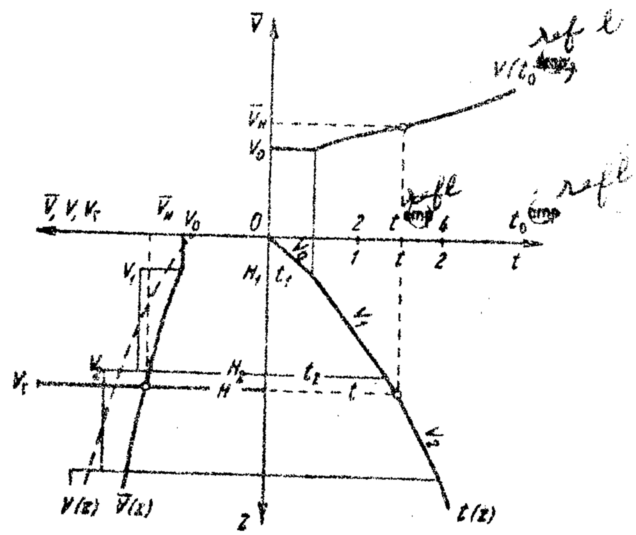


Fig. 72. Vertical hodograph $t(z)$ and graphs of dependences of velocities on the depth z and time of arrival of reflection t^{refl}, $\overline{V}(z)$ and $\overline{V}(t^{refl})$ are graphs for the average velocity. The graphs of the lower velocity $V(z)$ -- summary velocity column -- are given in two forms: smooth curve (dotted) and staircase line. On the diagram $t_0^{refl} = t/2$; $V_1 = (H_2 - H_1)/(t_2 - t_1)$; $V_H = H/t$.

However, in the method of refracted waves (CMRW) one is forced more frequently to solve this problem without having corresponding hodographs of reflected waves. In this case the problem becomes somewhat more complicated owing to the fact that in the method of refractions the "time at explosion point" t_0 (Fig. 73) is connected with the depth and the velocities by a more complicated relationship than the analogous quantity (t_0^{refl}) in the method of reflected waves.

The solution of this problem is found in the textbook ([58], p 342). We give give below another somewhat simpler solution.

Let us assume that there are given hodographs of only refracted waves and these are used to determine the times t_0, intercepted by the continuations of these hodographs on the time axis, passing through the corresponding points of explosion (or that the lines $t_0 = t_0(x)$ by opposite hodographs have been determined). We start out with the assumption that the medium is horizontally stratified, and we shall use the method of average velocities, i.e., we shall assume arbitrarily that the rays are straight, although the average velocity depends on the depth: $\overline{V} = \overline{V}(z)$. In addition, we shall assume the value of the boundary velocity V_b to be known for the sought boundary; it is not necessary to know the value of $\overline{V}$ in order to determine it by the method of "difference hodograph" as outlined in pages 134 -- 138 [of source].

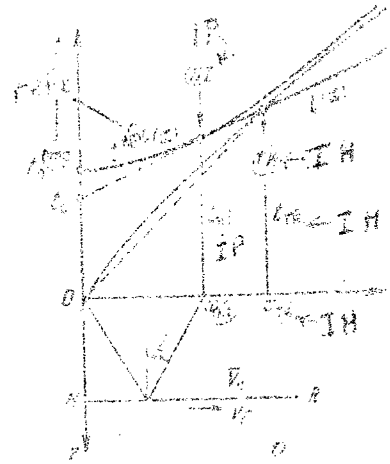


Fig. 73. Used in the determination of the depth H and the average velocity $\bar{V}_H = \bar{V}(H)$ for a refracting boundary at a known law of average velocities $\bar{V}(z)$, provided one knows the time t_0, intercepted by the continuation of the hodograph of refracted waves on the time axis, and the value of the boundary velocity V_b; IP -- initial point of the hodograph of reflected waves; IH -- point of intersection of hodographs.

Our problem consists of determining, for a given value of the time t_0, the corresponding value of H of the depth z and to find the value of the velocity $\bar{V}_H = \bar{V}(H)$.

For this purpose we first solve the opposite question: given the values $z = z_i$, to which correspond the definite values $\bar{V}(z_i) = \bar{V}_i$ $(i = 1, 2, 3, \ldots)$, let us calculate the corresponding values $t_0 = t_{0i}$ and let us plot the graph of the relation between t_0 and H, and also between t_0 and $\bar{V}$.

This graph will serve as a nomogram for solving the direct problem.

The nomogram is calculated in accordance with the well known formula for the time t_0 at the point of explosion, when the depth of the refracting boundary $z = H$ is known along with the velocity in the covering ($\bar{V}$) and the underlying (V_b) medium (see, for example, [5], 387):

$$t_0 = \frac{2H}{\overline{V}} \cos i, \tag{7}$$

where

$$\sin i = \frac{\overline{V}}{V_b} \tag{8}$$

In this case it is assumed that $\overline{V}$ depends on z (=H).

Having specified definite gradually increasing numerical values of z_i of the depths z, we find from the graph $\overline{V}$ (z) the corresponding values of $\overline{V}_i$ of the average velocity $\overline{V}$, and then, using the formulas (7) and (8), we calculate the corresponding values t_{0i} of the times t_0.

The pairs of values (t_{0i}, z_i) and $(t_{0i}, \overline{V}_i)$ make it possible to plot point by point two curves: in the former cases -- the relationship $H = H(t_0)$ (here H has the same meaning as z), and in the second the relationship $\overline{V} = \overline{V}(t_0)$.

Both curves can be unified, as shown in Fig. 74, by putting two kinds of markers on the ordinate scale, one for the depth H and one for the velocities $\overline{V}$. This is more convenient in the use of this graph for the construction of sections (see Section 4).

In order to determine the values of $\overline{V}$ and H for different possible values of V_b, for different boundaries, or for one boundary with a varying velocity V_b, it is necessary to plot on the graph a series of curves, corresponding to different values of V_b = const, i.e., to show a family of curves with parameter V_b. This is shown in Fig. 74.

We note that a curve with parameter $V_b =$ coincides with the curve $H = H(t_0^{refl})$ and respectively $\overline{V} = \overline{V}(t_0^{refl})$ for the hodographs of the reflected waves.

Determination of average velocities $\overline{V}$ by the initial points of hodographs of refracted waves. If it becomes possible to separate by means of the seismograms and to note on the hodographs the initial points of the hodographs of the refracted waves (point IP on Fig. 73), then these points can be used to determine the average velocities ahead of the refracting boundaries. *

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* Strictly speaking, here one determines, as by means of the hodographs of the reflected waves [58], not the average but the effective velocities, which are precisely equal to the average velocities only for known ideal conditions (covering medium homogeneous etc.). However, under conditions which are most frequently encountered in practice, the effective velocities usually differ little from the average ones and can be assumed in place of the average ones without introducing corrections ([56], pp 66 -- 75). The dependence of the effective velocities and the different factors is considered in articles [31, 33].

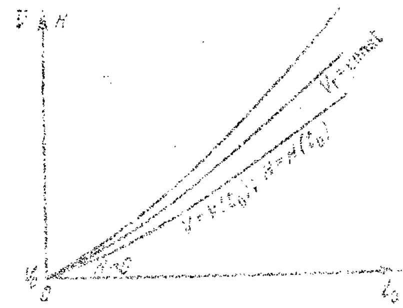

Fig. 74. Diagram of a nomogram for the determin tion of the depth H of the refracting boundary and the average velocity $\overline{V}$, if the times t_0 are specified and the boundary velocities V_b are known. The average velocity changes with depth in accordance with a known law, corresponding to which this nomogram should be constructed.

The average velocity $\overline{V}$, according to [42], is determined by the following formula (see also [58], p 303):

$$\overline{V} = \sqrt{\frac{x_{IP} V_b}{t_{IP}}} \tag{9}$$

Here x_{IP} and t_{IP} are the coordinates of the initial point (Fig. 73); V_b is the boundary velocity (it is assumed known, as in the preceding case).

Formula (9) is accurate provided the boundary is horizontal and the covering medium is homogeneous. However, even at sufficiently considerable deviations from these ideal conditions, this formula usually leads to satisfactory results.

Thus, if the boundary if not horizontal and its angle is φ, then in this case the average velocity $\overline{V}$ is

$$\overline{V}_\varphi = \sqrt{\frac{x_{IP}\, T\, V_D}{\tau_{IP}}}\cos\varphi .$$

It is impossible to determine $\overline{V}$ directly from the latter formula, since the angle φ can be obtained only as a result of constructing the section, for which it is necessary to know $\overline{V}$ beforehand. But a compar son of this formula with the preceding one (9) makes it possible to estimate the systematic error in the determination of $\overline{V}$ by means of formula (9), which depends on the inclination of the boundary. The calculations lead to the following Table 7.

TABLE 7

Relative error $\delta \overline{V} = (\overline{V} - \overline{V}_\varphi)/\overline{V}$ in the determination of the average velocity $\overline{V}$ by means of formula (9), depending on the angle of inclination of the refracting boundary [42].

φ in degrees.	0	10	15	20	25	30
$\delta \overline{V}$ in percent.	0	0.8	1.6	3.1	4.6	7.0

It follows from Table 7 that even at considerable angles of inclination of the boundary, approximately up to 20%, the systematic error in the determination of $\overline{V}$ by means of formula (9), which depends on this inclination, does not exceed ordinary random errors of single determinations of the value V by hodographs of the reflected waves.

An idea of the possible magnitude of the random error in the determination of $\overline{V}$ by the coordinates of the initial points (x_{IP}, t_{IP}) is given by the following example [42]. If the relative errors of the arguments are $\delta x_{IP} = 5\%$, $\delta t_{IP} = 2\%$, $\delta V_b = 3\%$, the angle $\varphi = 20^\circ$, and its error is $\Delta\varphi = 5^\circ$, then the relative error in the value of $\overline{V}$ is $\delta \overline{V} = 3.2\%$

A similar examination of the errors in the determination of $\overline{V}$ by initial points of the hodographs of refracted waves and a comparison with the errors in the determination of $\overline{V}$ by the hodographs of reflected waves is found in reference [36]. The general conclusion is that the determination of $\overline{V}$ by initial points is inferior in accuracy to the determinations by hodographs of reflected waves, although usually by not much.

However, the principal obstacle to an extensive systematic application of the considered method for work in CMRW is not the failure in accuracy -- this accuracy is usually satisfactory, but the fact

that a reliable discrimination of the initial points can be carried out only under particularly favorable seismogeological conditions, which are relatively rarely encountered.

Determination of average velocities $\bar{V}$ from the points of intersection of the hodographs. For lack of other more reliable data, an approximate value of the average velocity $\bar{V}$ can be obtained by the coordinates (x_{IH}, t_{IH}) of the points of intersection of the hodographs, corresponding to this boundary, up to which the average velocity is determined, and the covering medium, as well as the preceding branch of the hodograph, corresponding to the refracted waves in a certain sublayer in the covering layer, or else the direct wave in the covering layer as a whole, if the velocity in it changes with depth monotonically and sufficiently smoothly (Fig. 73). The velocity $\bar{V}$ is calculated in accordance with the following formula, which has long been used in practice in the method of refracted waves

$$\bar{V} = \frac{x_{IH}}{t_{IH}} \tag{10}$$

According to this formula, the average velocity $\bar{V}$ ahead of a given refracting boundary is determined by the slope of the line drawn from the origin 0 (point of explosinn) to the point IH of the intersection of the hodographs. Naturally, one must introduce in the observed hodographs also the corresponding corrections, as indicated above (see also Fig. 75).

Formula (10) is accurate provided the covering medium is homogeneous. But calculations for certain cases of a stratified covering medium with constant layer velocities V_i ($i = 1, 2, 3, \ldots$) in each of the layers show that under the ordinary relations encountered in practice between the thicknesses and velocities in the layers, the errors in the determination of $\bar{V}$ by formula (10) are usually not very large. Thus, in the case of a double layer covering medium with thicknesses of layers h_1 and h_2 and velocities V_1 and V_2, and $V_1/V_2 = 0.5$ and $h_2/h_1 > 5$, with changing velocity V_b in the considered refracting layer over a wide range ($V_1/V_b > 0.1$) the errors in the determination of $\bar{V}$ do not exceed 10%; at $h_2/h_1 \ll 1$ these errors may, however, reach 20% and more.

Comparison of different methods of determining $\bar{V}$. The most accurate data on the average $\bar{V}$ (and also on the layer velocities) in prospecting by the CMRW are obtained, as in the method of reflected waves, with the aid of seismic coring.

Somewhat less accurate, but also fully reliable data (under favorable conditions) are obtained with the aid of the interpretation of hodographs of reflected waves. To obtain such data it is naturally necessary to accompany the work on the CMRW by observations by the method of reflected waves (combination).

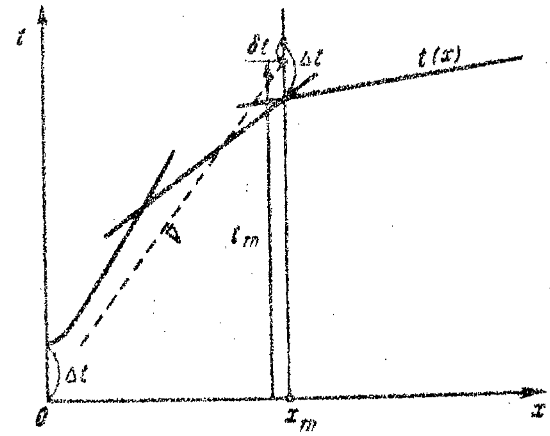

Fig. 75. Determination of the average velocity $\overline{V}$ on the basis of the point of intersection of hodographs. The average velocity corresponding to the boundary from which the hodograph t(x) is obtained, is determined by the formula $\overline{V} = x_{TH}/t_{TH}$. The time t_{TH} is the time at the point of intersection, corrected for the depth of the charge correction (Δ t) and for the difference in the phase from the arrival (correction δ t).

The next accurate method of determining the average velocities $\overline{V}$ is the use of initial points of hodographs of refracted waves. The use of this method, as indicated, is limited essentially by the fact that the separation of the initial points can be carried out only under conditions that are particularly favorable for this purpose from the seismogeological point of view.

Finally, the least accurate, but the most universal method of determination of $\overline{V}$ is by calculating this quantity from the points of intersection of the hodographs.

If data of the velocities $\overline{V}$ over a certain section of the investigated territory have been obtained by a more accurate method, it is naturally necessary to consider these as the reference data and have them serve as a basis of the interpretation of the hodographs of refracted waves in the construction of the sections. In this case, however, one cannot neglect data which make it possible to determine velocity V with lesser accuracy. A comparison of these determinations with the more exact ones will allow a more justified use of approximate methods, when it becomes necessary to resort to them as the distance to the places where the reference data are known is increased.

Compilation of summary data on the velocities in the covering medium. In the CMRW, as in the method of reflected waves, individual determinations of the average velocity $\bar{V}$ (and other velocities) in the covering medium, with the exception of seismic carottage, usually have low reliability. Owing to the lack of other data these must be used only at the beginning, in the preliminary interpretation at the start of seismic prospecting observations in a new region. Later on, as material is accumulated (hodographs of reflected and refracted waves) and determinations are made from these of the average velocities $\bar{V}$, these data must be summarized in a definite manner and averaged, and only then can they be used in such a generalized form for further interpretation of hodographs: in the construction of the sections and in the compilation of structural maps.

There exists two principal methods of compilation of summary data on velocities: the first -- the compilation of summary velocity sections, characterizing the dependence of the average velocity $\bar{V}$ (z) and layer velocity V (z) on the depth z. The second is the compilation of graphs $\bar{V}$ (x) or maps $\bar{V}$ (ξ, η) of average velocities, characterizing their variations as functions of the horizontal coordinates along the profiles or routes (x) or over the area (ξ, η). The first method is applicable preferably in prospecting at medium and great depths, where usually several boundaries are constructed; the second is used in prospecting at small depths and for a small number (usually one or two) boundaries under conditions of great variability of the velocities in the covering layer at different sections.

These two methods can also be combined, particularly in detailed area prospecting.

a) Summary velocity column. This name** is taken to mean an aggregate of graphs of the dependence of the average $\bar{V}$ and layer v vel velocities on the depth z (Fig. 72, left lower part of the diagram), compiled as a result of the generalization of the data on the velocities, obtained within the limits of a certain region with velocity structure of uniform type. On the same diagram one plots later on the data on the boundary velocities V_b

In the compilation of the summary velocity column by data of field seismic observations, the initial graph is compiled by points which are the results of the processing of individual determination of pairs of quantities: average velocities $\bar{V}$ and corresponding depths z = H. By way of such a starting graph it is convenient to use a verticalhodograph t = t (z), where $t = z/\bar{V}$. On this graph one plots, marked by different symbols, the points (z_i, t_i); i = 1, 2, 3, ..., obtained as a result of the determinations of $\bar{V}$ and z = H, either by

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** Analogously: summary stratigraphic (or lithological) column -- a term used in geology and geological prospecting.

different methods (by hodographs of reflected waves, by initial points, and by points of intersection of hodographs of refracted waves, and if these are available, also by seismic coring data), or else under different conditions (when the upper part of the section, judging from the geological data or from the velocities determined by the first branches of the hodographs, is represented by different rocks). The introduction of different designations makes it possible in the former case to give a relative estimate, by means of different methods, of the determinations of V in local conditions, and in the second -- as convincing data are accumulated it is possible to carry out the separation of the regions with substantially different velocity columns.

The aggregate of the points obtained (z_i, t_i) is averaged on the graph by either drawing a smooth curve, or a broken line, depending on what kind of law is proposed to be obtained for the variation of the layer velocity V with depth z. The first method corresponds to a continuous law $V = V(z)$, the second to a step-like law: V_k = const, $k = 1, 2, 3, \ldots$.

The choice of any particular law is determined primarily by the requirement of better correspondence between observations.

On the basis of the average graph (curve or broken line) of the vertical hodograph $t(z)$, one plots the remaining graphs, shown in Fig. 72, namely: for the dependence of the average and layer velocities on the depth $\bar{V}(z)$ and $V(z)$ (velocity column), and for the dependence of the average velocity on the time of reflection against the point of explosion $\bar{V}(t_0^{refl})$.

The values of V for the construction of the graphs V (z) are determined as apparent velocities over the vertical hodograph $t(z)$. If the graph $V(z)$ are obtained in the form of a staircase line, then the values of the layer velocities V_k = const are determined, within the limits of the corresponding intervals, from the inclination of the straight-line segments, of which the vertical hodograph consists in this case.

One also enters in the summary velocity column the data on the boundary velocities V_b, obtained at definite depths, based on the results of the interpretation of the hodographs of the refracted waves on the longitudinal profiles. The compilation of the graph of the layer velocities $V = V(z)$ with values of the boundary velocities makes it possible sometimes to judge the degree of reliability of the initial graphs -- the vertical hodograph $t = t(z)$ or the law of average velocities $\bar{V} = \bar{V}(z)$. The layer velocities V cannot be greater than the boundary velocities V_b in layers located at one and the same depth; this follows from the physical meaning of both types of velocities. If it is found that the layer velocity, calculated on the basis of the vertical hodograph or the graph of average velocities, exceeds the boundary velocities at the same depth, then the assumed law $t = t(z)$ or $\bar{V} = \bar{V}(z)$ should be reviewed and corrected with the aid of certain changes in the direction of the averageing curve.

On the basis of the summary graph of the average velocities $\bar{V} = \bar{V}(z)$, one plots the curves $\bar{V}(t_0)$ and $H(t_0)$ for definite values

of the boundary velocities V_b (Fig. 74), with the aid of which one compiles the sections and the structural charts.

For portions where the velocities change with depth essentially in different manners, it becomes necessary to compile separate velocity columns. Here it is necessary to strive, wherever possible, towards an increase in the dimensions of the section, in which it is proposed to use the same velocity column, particularly if the individual termination do not yield sufficiently clear or a systematic picture of the distribution of velocities in the space. When interrelating the sections and the structural charts, constructed on the neighboring sections through the use of different velocity columns, the necessity arises naturally of res rting to interpolation, which com licates the work.

b) Graphs $\bar{V}$ (x) and charts $\bar{V}$ (ξ η) of the variation of the average velocities along the profiles and over the area. Such graphs and charts are compiled separately for each of the prospected boundaries.

The graph of variation of the average velocity along the profile $\bar{V}$ (x) is plotted point by point (x_i, $\bar{V}_i$), i = 1, 2, 3, ..., where $\bar{V}_i$ is the value of the average velocity obtained as a result of the individual determination, and x_i are the coordinates (stations) of the points of the profile, to which these values pertain. The points x_i are selected in the middle of the interval of the profile, on which the determination of $\bar{V}_i$ is carried out. Thus, in the determination of $\bar{V}$ by single hodographs of reflected waves, x_i is taken half way between the point of explosion and the center point of the interval of observation of reflection; if $\bar{V}$ is determined on the basis of the initial point or the point of intersection of the hodographs of the refracted waves, it is taken half way between the point of explosion and the corresponding point.

The aggregate of such points (x_i, $\bar{V}_i$) obtained on the profile is generalized by drawing a broken or a smooth curve between those points, and the probable errors are taken into account -- one leaves our the deviations of the individual insufficiently reliable points from the averaging line.

In the case of area surveys by means of a network of longitudinal profiles, from which the velocities $\bar{V}_i$ are determined, the result of the generalization is presented in the form of a chart with isolines of $\bar{V}$. For this purpose, use is made of graphs $\bar{V}$ (x), plotted on the basis of the profiles. In the presence of mutually controllable data, for example in places where the profiles come together and intersect each other, a further averaging is carried out in the distribution of the value of $\bar{V}$ over the area. The isolines of $\bar{V}$ are drawn smoothly, without details due to deviations of individual determinations of $\bar{V}_i$ from the overall picture, provided these deviations lie within the limits of possible errors.

Let us note that in this method of expressing the velocities $\bar{V}$ asfunctions of the horizontal coordinates the variations of the velocities $\bar{V}$ with the depth z or respectively with the values of t_0 are

automatically taken into account, although this is not expressed in explicit form in this scheme of processing of the observations. However, the values of the depth z_i (= H) which are calculated simultaneously with $\bar{V}_i$ are left in this method outside the averaging operation; the possibility of compiling generalized dependences of $\bar{V}_i$ and z_i is not used. This represents a certain shortcoming in this method of generalization as compared with the preceding one (for the case of $\bar{V}$ (z)). Another shortcoming is the impossibility of obtaining in this manner information on the layer velocities, which describe better the physical properties of the rocks, than the average velocities, which have a rather formal meaning. Therefore, using this method, it is best to represent the data also by the first method. Here, possibly, it will become necessary to compile different velocity columns for different sections, taking into account the features of their geological structure.

In the compilation of many individual determinations of $\bar{V}$ and H on the profile, the results may be represented in the form of a graph plotted in coordinates x and z, where the function $\bar{V}$ (x, z) is represented by its isolines. On this graph it is possible to perform the operations of averaging, and on the basis of the average graph of $\bar{V}$ (x, z) it is possible to plot the graph of distribution of the layer of velocities V (x, z) on the corresponding cross section. A more complicated manner is the graphic representation of the behavior of $\bar{V}$ over the area with allowance for the variation of this quantity with depth, i.e., the representation of the function $\bar{V}$ (ξ, η, z); it would require a series of graphs. In this case one could also carry out the averaging and plot the graphs that represent the behaviorof the layer velocities V (ξ, η, z) in the space. However, usually the factual material is insufficiently abundant for so great a detailing of the velocity structure of the medium. In this connection, it becomes necessary in practice, as a rule, to restrict oneself only to the two foregoing simple schemes of averaging and generalization of the data on the velocities in the covering medium. From these one chooses, as the basic material, the one that best satisfies the local conditions, which in turn can be used for its supplementation as the factual material is accumulated.

4. Construction of Sections by Approximate Methods

In the method of refracted waves (CMRW) the construction of seismic sections consists, firstly, of determining the depths and the relief of the refracting boundaries, and secondly of determining the boundary velocities V_b.

When using the principal assumptions adapted in the CMRW, of the principal methods of the construction of sections by longitudinal profiles -- "the method of difference hodograph" and "the method" -- one determines first the boundary velocities V_b, and this is followed by the construction of the corresponding boundary.

The boundary velocity V_b can be determined either on the basis of opposing hodographs or on the basis of overtaking hodographs. The boundary can be constructed on the basis of either the same opposing hodographs, or on the basis of hodographs directed to one side (individual or overtaking). The use of opposing hodographs for the determination of V_b and for the plotting of the relief of the boundary yields, as a rule, more reliable results than the use of hodographs in only one direction.

The average velocity $\bar{V}$ in the covering medium is assumed to be known; the methods of its determination are described in the preceding section. The values of V are used in the approximate method only for the construction of the boundary, and not for the determination of the boundary velocities V_b.

Determination of the boundary velocity V_b by the method of different hodographs. * The use of this approximate method is limited by the requirement that the angles of inclination of the refracting boundary be not too large, that the deviations of its shape from a plane not to be great, and that the velocities in the covering medium and the boundary velocity V_b along the profile not be too strong and frequent.

a) Case of opposing hodographs. The branches of these hodographs should intersect each other mutually at a certain section of the profile.

Assume that there are available opposing hodographs $\overrightarrow{t}(x)$ and $\overleftarrow{t}(x)$ of refracted waves, corresponding to one and the same boundary R. Let us assume initially that the branches of these hodographs overlap over the entire section of the profile between the corresponding points of explosion O_1 and O_2 (Fig. 75). Such a complete overlap is feasible in practice, if each of the opposing hodographs is accompanie d by an overtaking hodograph, which makes it possible to complete it to the corresponding point of explosion. We shall see later on that complete overlap is not always necessary; nor is it always necessary that the opposing hodographs reach their points of explosion or the mutual points.

We shall call a different hodograph $t_d(x)$ the curve expressed by the expression

$$t_d(x) = \overrightarrow{t}(x) - \overleftarrow{t}(x) + T \qquad (11)$$

or in a different form

$$t_d(x) = \overrightarrow{t}(x) + [T - \overleftarrow{t}(x)] \qquad (12)$$

* The method of difference hodograph for the determination of boundary velocities V_b on the basis of hodographs with overlapping branches was proposed by G.A. Gamburtsev; this method can be generalized to include also the case of overtaking hodographs.

According to (12) the difference hodograph is constructed on the basis of specified hodographs $\vec{t}(x)$ and $\overleftarrow{t}(x)$ in the following manner (Fig. 76). For any point M of the profile with coordinate x_M we measure the section $\overline{de} = t$ from one of the hodographs $\overleftarrow{t}(x)$ to the horizontal line EC, which joins the mutual points, and plot it upward $\overline{bc} = \delta t$ from the second hodograph $\vec{t}(x)$. We obtain the corresponding point c of the difference hodograph.

Another method of construction, frequently used in practice, consists of measuring the sections along the time axis between the opposite hodographs and of plotting these sections as ordinates of the "difference hodograph" from the abscissa sxis -- the profile line. In this version of construction one determines, strictly speaking, only the slope of the curve of the difference hodograph $t_d(x)$ (formula (11)), but not its position along the time axis. However, in view of the fact that the boundary velocity V_b is calculated precisely from the slope of the curve $t_d(x)$ (see below), this method of construction in the case of overlapping opposing hodographs accomplishes its purposes. The advantage of this method lies in the fact that there is no need in its application for the knowledge of time T in the mutual points.

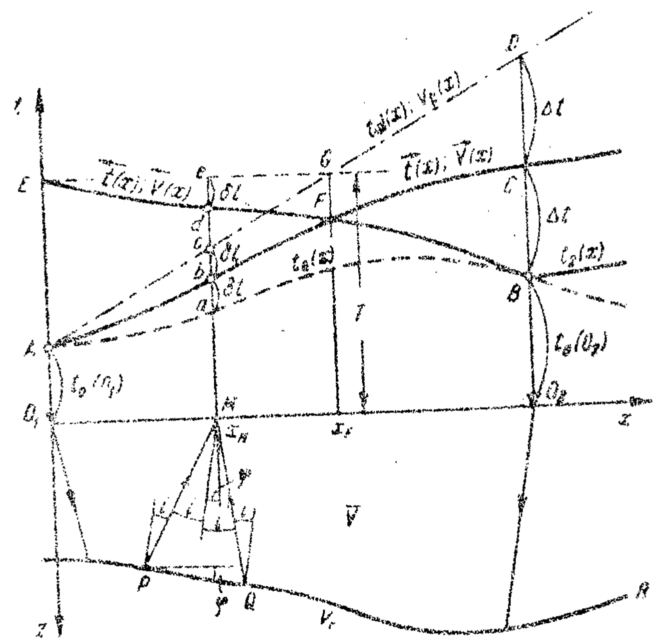

Fig. 76. Determination of the boundary velocity V_b by the method of difference hodograph $t_d(x)$.

The start of the difference hodograph t_d (x) will be arbitrarily considered to be the point A, where it intersects the line t_0 (x).

We recall that to construct the line t_0 (x) the same section $\overline{ac}$ = t is plotted downward $\overline{ab}$ = t, from the second hodograph $\vec{t}$ (x). In view of this it is found that the hodograph $\vec{t}$ (x) represents a line that bisects the vertical sections between the line t_0 (x) and the difference hodograph t_z (x) with an origin at the point A "above" the corresponding point of explosion.

We note furthermore that the difference hodograph t_d (x) with an origin at the point A (Fig. 76) intersects the line EC, which joins the mutual points, at the point G, which lies on the same vertical as the point F of the mutual intersection of the opposite hodographs $\vec{t}$ (x) and $\overleftarrow{t}$ (x).

We shall show now that the boundary velocity V_b is approximately equal to twice the apparent velocity V_d, determined by the difference hodograph, if the angle φ of the inclination of the boundary is small. The difference hodograph permits thereby to determine readily the boundary velocity V_b.

For the proof, let us differentiate the Eq. (11) with respect to x

$$\frac{dt_d(x)}{dx} = \frac{d\vec{t}(x)}{dx} - \frac{d\overleftarrow{t}(x)}{dx}. \qquad (13)$$

The terms of this equation are respectively equal to the reciprocals of the apparent velocities V_d, $\vec{V}$, and $\overleftarrow{V}$, in the difference t_d (x), direct hodograph $\vec{t}$ (x), and reverse hodograph $\overleftarrow{t}$ (x). These velocities are in turn equal to

$$\begin{aligned} V_d &= V_d(x) = 1 : \frac{dt_d(x)}{dx}; \\ \vec{V} &= \vec{V}(x) = 1 : \frac{d\vec{t}(x)}{dx} = \frac{V}{\sin(i+\varphi)}; \\ \overleftarrow{V} &= \overleftarrow{V}(x) = 1 : \frac{d\overleftarrow{t}(x)}{dx} = -\frac{V}{\sin(i-\varphi)} \end{aligned} \qquad (14)$$

(See Fig. 76, and also [14, 62]. Inserting (14) into (13) and considering that

$$V_b = \frac{\bar V}{\sin i},$$

we obtain

$$d \longrightarrow \frac{1}{V_p} = \frac{1}{\overrightarrow{V}} - \frac{1}{\overleftarrow{V}} = \frac{\sin(i+\varphi)}{\bar V} + \frac{\sin(i-\varphi)}{\bar V} = \frac{2\sin i \cdot \cos\varphi}{\bar V} = \frac{2\cos\varphi}{V_b}$$

and we next obtain a formula for the boundary velocity

$$V_b = 2V_d \cos\varphi, \tag{15}$$

This formula is correct for any value of φ and gives the exact result for the point x_M of the profile, if within the limits of the triangle PQM (Fig. 76) the quantities $\bar V$, V_b and φ are constant, i.e., in particular, if on the section PQ the boundary is plane. However, it cannot be used directly, since the angle φ is not known beforehand. * If it is known nevertheless that this angle is small, then $\cos\varphi \approx 1$, and we obtain finally the approximate computation formula

$$V_b = 2V_d \tag{16}$$

for small φ, which no longer contains unknown quantities in the right half. When $\varphi = 10^\circ$ Eq. (16) gives a relative error of 1.5% in the determination of V_b, at $\varphi = 15^\circ$ the error is 3.5% and at $\varphi = 20^\circ$ it is 6%.

Thus, with this methof of "difference hodograph" it is possible to determine quite accurately the value of V_b without knowing the value of $\bar V$ in the covering medium and without knowing the value of the angle φ of inclination of the refracting boundary, provided this angle is not too large, and does not exceed tentatively 15°

Let us note certain singularities of this method.

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* This difficulty has no principal character. Knowing the velocities $\overrightarrow{V}$ and $\overleftarrow{V}$ in the opposing hodographs, and also the velocity $\bar V$ in the covering medium, it is possible to determine the angles i and φ from the well known exact formula (see, for example, [14, 62]): $\sin(i - \varphi)\ \bar V/\overrightarrow{V}$, $\sin(i + \varphi)\ \bar V/\overleftarrow{V}$, and to find $V_b = \bar V/\sin i$. These formulas are correct provided all quantities are constant, particularly if φ = const -- the boundary is plane.

We emphasize above all that the requirement that the boundary be plane pertains, for each point x_M of the profile, only to the corresponding section PQ of the boundary R (Fig. 76). In view of this it is enough to stipulate that the boundary differ little from a plane only over the extent of similar relatively small sections, (of length on the order of the depth of the boundary), and as a whole the boundary can be substantially not plane. Here it is assumed that the rays of the waves propagating with the velocity V_b glide along the boundary, and do not penetrate within the underlying layer.

Furthermore, the value of the boundary velocity, corresponding to the point x_M of the profile, as obtained by formula (16) also pertains to this section PQ. It follows therefore that the practical boundary velocity V_b may be, generally speaking, variable, but within the lengths of the sections similar to PQ, its changes should not be large.

Calculations show furthermore that the requirement $\overline{V}$ = const may be violated within certain limits without essentially affecting the values of V_b determined by this method. * The method remains applicable in practice in cases when the average velocities depend on the depth, $\overline{V}$ (z) and on the horizontal coordinates $\overline{V}$ (x).

Finally, an important property of this method is that it is almost entirely insensitive to inhomogeneities and to other peculiarities in the structure of the medium, pertaining to the uppermost portion of the section -- to the zone of small velocities, to the topographic relief, and to the conditions of installation of the seismographs. When the difference hodograph is plotted, the local deviations of the points of opposing hodographs, due to these peculiarities, cancel each other out. The form of the difference hodograph is found to be free of the influence of these peculiarities, and the spread in the points on the hodograph is less than on each of the opposing hodograph individually.

Let us proceed to note of more particular character. If the opposing hodographs are not accompanied by overtaking hodographs and do not overlap over the entire section of the profile between the corresponding points of the explosion O_1 and O_2, but only on a part of it, but the time T at the mutual points, and consequently also the position of the line EC, is known, then the construction of the difference hodograph t_d (x) with origin at the point A does not differ from that described above. Here the hodograph t_d (x) will be obtained, naturally, only on that section of the profile, where the branches of the opposing hodographs overlap and will not reach the point A of its origin.

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* A slight dependence of the calculated values of V_b on $\overline{V}$, both for $\overline{V} = \overline{V_i}$ = const (i = 1, 2, 3, ...,) and for $\overline{V} \neq$ const, is inherent not only in this approximate method, but also in other more accurate methods of calculation.

If, furthermore, the time T and therefore also the position of the line EC, is unknown, the section analogous to $\overline{de}$ on Fig. 76 can be measured from any line parallel to the x axis. Sometimes it is logical to do so also in other cases. The difference hodograph will then be found to be generally shifted along the t axis, and its origin will be transferred from the point A to another point, namely to that point, where it intersects the line $t_0(x)$. The position of this point may also remain unknown. The slope of the difference hodograph does not change with such a transfer, and consequently this is not reflected in the method of determining the boundary velocity from this hodograph.

The difference hodograph is constructed for the most part by points, which are practically plotted usually less densely than the points corresponding to the locations of the seismographs on the profile. To determine the boundary velocities $V_b \approx \tilde{V}_b$ the aggregate of the points of the difference hodograph is unified with averaging within the limits of the permissible "spread" of the points by drawing either one straight line, common to the entire process section of the profile, or by a broken line, preferably with a small number of breaks.

The straight line sections of this line separate the sections of the profiles and respectively the boundaries where the boundary velocity V_b is considered constant. Consequently the dependence V_b on the place on the profile, $V_b = V_b(x)$, is represented in the form of a piecewise-constant function.

This method of processing the observations can be used, in particular, in seismic mapping of rocks, which are located directly below the surface of the refracting boundary.

b) <u>Case of overtaking hodographs</u>. Let us show that two overtaking hodographs $\overrightarrow{t}(x)$ and $\overrightarrow{t_2}(x)$ (Fig. 76), extended to the corresponding explosion points O_1 and O_2, suffice for an approximate determination of the boundary velocity V_b under the assumption that this velocity is constant on the section of the profile between the explosion points O_1, O_2. The approximateness is due as before to the principal requirement that the angles φ of the inclination of the refracting boundary be small.

Let us turn again to Fig. 76, where we shall now consider the opposing hodograph $\overleftarrow{t}(x)$ to be missing; all that are given are the hodographs $\overrightarrow{t}(x)$ and $\overrightarrow{t_2}(x)$.

In the case of a constant boundary velocity the difference hodograph $t_d(x)$ should represent a straight line. To determine it it is enough to have two points. The first point, lying in the difference hodograph, is known: this is point A, where the first hodograph $\overrightarrow{t}(x)$ intersects the time axis, passing through the point O_1 -- the corresponding explosion point. The second point is constructed in the following manner.

We measure the segment $\overline{BC} = \Delta t$ on the time axis, drawn through the point O_2, intersected by the specified hodographs $\overrightarrow{t_2}(x)$ and $\overrightarrow{t}(x)$, and measure it upward from the hodograph $\overrightarrow{t}(x)$; $\overline{CD} = \Delta t$. The point D is the sought one.

Actually, it was shown earlier that the hodograph $\overrightarrow{t}(x)$ is a line that bisects all the vertical segments between the lines $t_0\ (x)$ and the difference hodograph $t_d\ (x)$ with origin at the point A. This holds also for the segment BC + CD on the vertical line drawn through O_2. Consequently, the point D belongs to the difference hodograph with origin at the point A.

By joining the points A and D with a straight line, we obtain the difference hodograph, the slope of which determines in a known manner -- formulas (15) and (16) -- the unknown boundary velocity V_b.

We now give a version of determining the boundary velocity V_b by the method of difference hodograph, with use of overtaking hodographs $\overrightarrow{t}(x)$ and $\overrightarrow{t_2}\ (x)$ and an opposing hodograph $\overleftarrow{t}\ (x)$, which are not plotted completely, but only on such sections, that the positions of the points B, C and F are determined (Fig. 76). One encounters such cases in practice, when the branches of the opposite hodographs on the sections AF and BF, which are adjacent to their points of explosion O_1 and O_2, are lacking.

In this case we readily find from the opposing hodographs the point G of the difference hodograph, which point lies over the point F of their intersection. On the other side, from the overtaking hodographs, as before, we determine the point D of the difference hodograph. At the same time this hodograph is determined under the assumption of linearity on the section GD, and from this one can find V_b.

We note that in the determination of V_b by the use of overtaking hodographs, as in the case of opposing hodographs, the approximateness of the method lies in the formula (16)

$$V_b = 2V_d$$

is approximately correct only for small angles φ of inclination of the boundary, but has no essential character. If the velocity $\overline{V}$ in the covering medium is assumed to be known, then by knowing the apparent velocity $\overline{V}$ from the hodograph $\overrightarrow{t}(x)$ and the velocity V_d from the difference hodograph, it is possible to determine V_b from the exact formulas, which are correct for any value of φ.

In fact, according to (15) and (8) we have

$$\cos\varphi = \frac{V_b}{2V_d} = \frac{\overline{V}}{2V_d \sin i}$$

hence

$$2\sin i \cos\varphi = \frac{\overline{V}}{V_d}$$

On the other hand, it is known [14] that

$$\sin(i+\varphi) = \frac{\overline{V}}{\overset{\leftarrow}{V}} \qquad (17)$$

Subtracting this equality from the preceding one, we get

$$\sin(i-\varphi) = \frac{\overline{V}'}{V_d} - \frac{\overline{V}}{\overset{\leftarrow}{V}} \qquad (18)$$

This system of Eqs. (17) and (18) makes it possible to determine readily the angles i and φ , and then the boundary velocity V_b can be obtained from the known formula

$$V_b = \frac{\overline{V}}{\sin i} \qquad (19)$$

Formulas (17) and (18) and (19) give the exact solution of the problem: determine V_b by means of overtaking hodographs of refracted waves, using the known values of the velocities $\overline{V}$, $\overline{V}'$, and V_d independent of the value of the angle φ . These formulas are valid provided all the quantities are constant, particularly φ = const -- the boundary is plane (see remark on p. 136 [of source]).

The foregoing method of determining the boundary velocity V_b by means of the difference hodograph, plotted on the basis of overtaking hodographs, differs substantially from the case of opposite hodographs in the fact that in the case of opposite hodographs the velocity V_b on the section of the profile, where their branches overlap mutually, can be determined as a variable quantity $V_b = V_b(x)$, whereas in the case of overtaking hodographs on the entire section between the two points, over which the difference hodograph is constructed, one determines only one, average value of this quantity V_b = const. This naturally narrows considerably the capabilities of the application of this method for a detailed investigation of the properties of the refracting layers (mapping, etc.).

Another shortcoming of this method is that in the case of overtaking hodographs, which do not represent a complete correlated system (Chapter III, Section 3), it is difficult to identify the phase of the waves obtained at different explosion points. This can lead to errors in the determination of the differences of the times, used in the given method for the construction of the difference hodograph, and corresponding to the errors in the determination of V_b. The relative error δV_b in the determination of V_b, due to an error Δt in the time when the phases are identified by the overtaking hodographs $t_1(x)$ and $t_2(x)$, is equal to

$$\delta V_b = \frac{\Delta t_{1,2}}{2(L/V_b)} \tag{20}$$

where L is the distance between the points of explosion O_1 and O_2. Thus, if V_b = 4 km/sec and L = 2 km, an error Δt of approximately one period of oscillations on the seismogram is possible, its value being $\Delta t_{1,2}$ = 0.03 sec, we obtain for V_b a possible relative error δV_b = 3%. In the case of opposing hodographs, errors of this kind are excluded, even if these hodographs are not reconciled in phase.

Thus, the determinations of boundary velocities V_b by overtaking hodographs are less detailed and less reliable than those with opposing hodographs with overlapping branches.

Nevertheless, the use of overtaking hodographs for the determination of V_b may be of interest, particularly under route-reconnaissance prospecting at relatively small depths in connection with the fact that the acquisition of the systems of overtaking hodographs necessary for continuous tracing of the boundary requires a lesser volume of work than the production of a system of summary opposing hodographs.

Concluding the examination of the method of determination of boundary velocities V_b with the aid of the construction of difference hodographs as being approximate methods, which do not require the knowledge of the velocities $\bar{V}$ in the covering medium, we note that both in the case of opposing and in the case of overtaking hodographs of refracted waves, an approximate determination of V_b is possible at variable velocities V_b; $\bar{V} = \bar{V}(z)$, $\bar{V}(x)$ etc., and also for a curved form of boundary; in this case the overtaking hodographs make it possible to determine only the average value of V_b on the section of the profile between the points of explosion. The region of possible application of this method is limited in practice principally to the requirement that the boundary not be too curved and that its slope angles not be too large; also important is that the variation of V_b along the profile not be too large and too frequent. These conditions are not satisfied, and also for the purpose of monitoring the results of the calculation of V_b by these approximate methods, one resorts to a determination of V_b by the exact method of time fields.

<u>Construction of the refracting boundary by the "t_0 method".</u> The t_0 method is one version of the method of "arithmetic means" [14]. By this method the refracaing boundary is constructed on the basis of specified hodographs, when the velocity $\bar{V}$ in the covering medium and the boundary velocity V_b are determined beforehand. For the construction of the boundary use is made of curves t_0 (x) "the times on the explosion point" for the hodographs of refracted waves.

a) Determination of the t_0 (x) lines. The t_0 (x) curves are determined either by opposing hodographs with mutually overlapping branches, or by hodographs without opposing overlaps -- individual, overtaking, etc.

The method of plotting the t_0 (x) curves in the case of opposing hodographs (within the limits of the region of mutual overlap of the branches) was described above (p. 134 [of source]). Here we consider the opposite case, in this case in order to construct the lines t_0 (x) we assume two curves to be specified: the hodograph t (x) which is subject to interpretation -- simple or summary -- and the difference hodograph t_d (x).

If the interpreted single hodograph $\vec{t}(x)$ represents that portion of one of opposing hodographs, which could not be interpreted previously in view of the lack of overlap by another opposing hodograph, then the difference hodggraph t_d (x) in the region under consideration can be obtained by extrapolation, by extension along the line of difference hodographs, constructed on the neighboring section of the profile on the basis of the overlapping branches of opposing hodographs.

If the processed hodograph $\vec{t}(x)$ is not included in the system of opposing hodographs, we shall assume first that the point A, where its continuation intersects the time axis (Fig. 76), is known. Then, inasmuch as the velocity V_b, by assumption is known, the difference hodograph t_d (x) is drawn in the form of a straight line passing through the point A with a slope calculated by the formula $V_d = V_b/2$. In the case of a series of overtaking hodographs the difference hodograph t_d (x) is plotted as indicated in p. 138 [of source].

The method of determining the lines t_0 (x) in the case shown in Fig. 76 a, follows from the previously established relation between the curves t_0 (x), t_d (x), and $\vec{t}(x)$: The curve $\vec{t}(x)$ bisects the vertical segments between the curves t_0 (x) and t_d (x) (Fig. 76, $\overline{ab} = \overline{bc} = \delta t$).

In view of this, the construction of the line t_0 (x) by means of an individual hodograph $\vec{t}(x)$ (or a difference hodograph t_d (x)) reduces to the following: for any point M of the profile (Fig. 76 a) we measure a segment of the time axis $\overline{bc} = \delta t$ between hodographs $\vec{t}(x)$ and t_d (x), and draw it downward from the specified hodograph $\vec{t}(x)$: $\overline{ab} = \delta t$. As a result we obtain the point A on the sought line t_0 (x). Doing this for a series of points on the profile, we plot the entire curve t_0 (x) point by point.

This rule can be also readily derived from an examination of the Eqs. (5) and (11), of the lines t_0 (x) and the difference hodograph t_d (x):

$$t_0(x) = \vec{t}(x) + \overleftarrow{t}(x) - T \qquad (5)$$

$$t_d(x) = \vec{t}(x) - \overleftarrow{t}(x) + T \qquad (11)$$

Eqs. (5) and (11) contain four functions: $\overrightarrow{t}(x)$, $\overleftarrow{t}(x)$, $t_0(x)$, and $t_d(x)$, to which four curves correspond on Fig. 76. If any two functions are specified, or any two curves, then the two remaining ones can be obtained by solving the system of Eqs. (5) and (11) or by means of a suitable graphic construction.

In view of the fact that in our case the reverse hodograph $\overleftarrow{t}(x)$ is assumed to be missing, we exclude the function $\overleftarrow{t}(x)$ from this system of equations. By adding (5) and (11) we obtain

$$t_0(x) + t_d(x) = 2\overrightarrow{t}(x)$$

from which we find the relation of interest to us

$$t_0(x) = 2\overrightarrow{t}(x) - t_d(x)$$

or in a different form

$$t_0(x) = \overrightarrow{t}(x) - [t_d(x) - \overrightarrow{t}(x)] \qquad (21)$$

Formula (21) indeed corresponds to the foregoing graphic construction.

In formulas (5), (11) and (21), and also in the graphic construction (Fig. 76 a) it was assumed that the origin of the difference hodograph $t_d(x)$ is at the point A, determined by the time $t_0(0)$ on the explosion point O. Through this point passes the extended hodograph $\overrightarrow{t}(x)$.

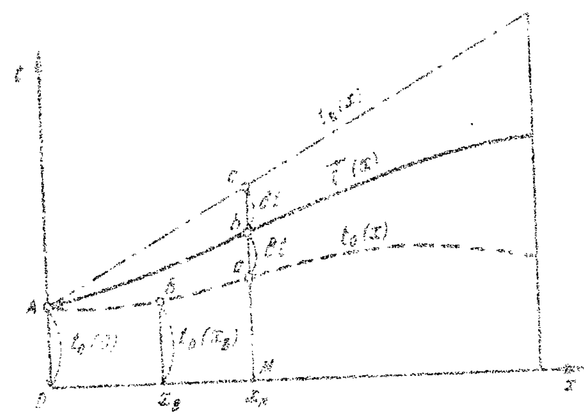

Fig. 76 a. Determination of the line $t_0(x)$ on the basis of an individual hodograph $\overrightarrow{t}(x)$ and a difference hodograph $t_d(x)$.

If the position of the point A is unknown (the hodograph $\vec{t}(x)$ and the line t_0 (x) do not reach the explosion point O and the difference hodograph t_d (x) has its origin at some other point), but at least one point B on the curve t_0 (x) is known, within that interval of the profile where the curves $\vec{t}(x)$ and t_d (x) have been determined, then this point B can be used instead of the point A as the origin for all the constructions. The given curves $\vec{t}(x)$ and t_d (x) are drawn through the point B by parallel transfer along the time axis, and then all the constructions are carried out in complete analogy with the preceding ones.

Finally, if not a single point on the curve t_0 (x) is known and the position of the difference hodograph along the t axis is not fixed, then the foregoing constructions will lead to a certain line, which represents the shape of the sought line t_0 (x), but shifted with respect to it by a certain unknown interval along the t axis. This makes it possible later on to determine the relief of the refracting boundary -- assuming the velocity $\bar{V}$ in the covering layer to be independent of the depth -- but does not make it impossible to determine the absolute depth of this boundary.

Concluding the examination of the methods of construction of the curves t_0 (x), we note that the construction of these curves by means of hodographs directed in one and the same direction is less reliable than the use of opposing hodographs with overlapping branches for this purpose.

In fact, in the case when hodographs of only one direction are used in a given segment, the resultant general slope of the line t_0 (x) depends greatly on the slope of the difference hodograph t_d (x), which was plotted beforehand. But in the absence of a profile of overlapping opposing hodographs on this segment, the very line t_d (x) itself must be drawn either by extrapolation, or on the basis of overtaking hodographs, which is less reliable than with opposing hodographs. This is also the cause of the lesser reliability of the construction of the curves t_0 (x) by means of single-sided hodographs.

Most frequently one obtains in the central portion of the profile overlapping opposing hodographs, and on the ends, when one of the opposing branches is terminated, there remains single branches. In accordance with this, the lines t_0 (x), and later on also the sections, will be characterized at different parts of the profile by a different degree of reliability. This must be noted on the drawings, by using different types of lines (heavy, thin, dotted,).

b) Construction of the boundary. The refracting boundary is constructed on the basis of the known lines $t_0 = t_0$ (x) and the values of the following velocities: $\bar{V}$ in the covering medium and V_b -- the boundary velocity.

The calculation of the depth H of the refracting boundary for each point of the profile is carried out, according to (7), by means of the formula

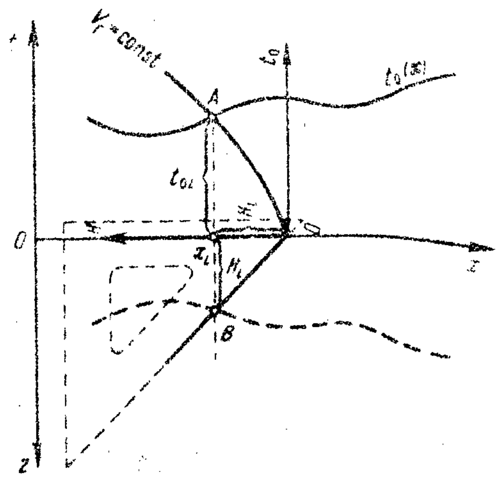

Fig. 77. Construction of the refracting boundary in the case when the velocity $\overline{V}$ in the covering medium depends on the depth z = H. For the graphic determination of the point B of the refracting boundary, which corresponds to the point A of the curve t_0 (x), the nomogram shown in Fig. 4 is provided with a straight line OB; this may be the side of a triangle, to which is glued the nomogram drawn on tracing paper.

$$H = \frac{\overline{V} t_0}{2 \cos i} \tag{22}$$

where sin i = $\overline{V}/V_b$. The formula (22) determines, strictly speaking, the depth along the normal to the refracting boundary. In order to go in the construction of the section from depths by normals to depths by verticals, it is possible to construct circles with radii H and centers at the corresponding points of the profile, and then find their envelope (see [14]). However, at small angles of φ of the inclination of the refracting boundary, on which the foregoing approximate methods of interpretation are indeed based, such a refinement is usually not required, and it is possible to assume that the depth H is equal to the depth along the vertical (for $\varphi \leq \sim 15^o$).

The values of the velocities $\overline{V}$ and V_b can be either constant ($\overline{V}$, $\overline{V_b}$ = const) or variable, $\overline{V}$ (z), V (x) and V_b (x). In the determination of the depth H = H_i at the point x x_i of the profile (i = 1, 2, 3, ...), in the case of variable velocities one uses those values which correspond to the same point on the profile.

If the calculations of the depths H are made under the assumption that the average velocity depends on the depth $\bar{V}(z)$, then the method described in p. 126 [of source] and the corresponding nomogram are used to reconcile t_0 with $\bar{V}$ and $\bar{H}$ (Fig. 74). If in this case the section is constructed on the same sheet of graph paper, where the lines $t_0(x)$ are drawn, and the distance axis for the graph $t_0(x)$ is made common with that for the section, then the operation of construction of the section can be carried out by using the procedure indicated in Fig. 77.

If V_b = const, it is also possible to draw directly the depths H from specified values of t_0, by preparing beforehand a rule (made of a folded sheet of paper), marked in values of t_0, corresponding to definite depths. The marking of such a rule is given with the aid of the nomogram of Fig. 74.

5. Construction of Sections by the Method of Time Fields

In the interpretation of hodographs of refracted waves by the method of time fields [49, 52, 53], the constructions are carried out in full accordance with the principles of geometric seismics. This, unlike the situation when the approximate methods are used (Section 4), does away with the limitations as regards angles of inclinations, shapes of refracting boundaries etc.

The initial data in the method of time fields are the observed hodographs and velocities of propagation of the waves in the covering medium. With this, the approximate representations of the "method of average velocities" (average velocity $\bar{V}$ variable, but the rays are straight) are discarded. The time fields, and, if necessary, the rays are constructed in accordance with the assumed law of distribution of the layer of velocities V in the medium.

Unlike the approximate methods (Section 4), where the boundary velocities V_b were first determined without allowance for the velocities in the covering medium, and then the refracting boundary was already plotted with allowance for these velocities, in the method of time fields the construction of the boundary precedes the determination of V_b, or else both are done simultaneously, each time with complete allowance of the velocities in the covering medium.

The practice of employing the method of time fields consists of solving the following particular problems:

a) The construction of isochrones of fields of the times of arrival of the fronts of the waves to different points of space, i.e., the determination of the positions of the fronts of the waves at different instants of time;

b) The determination of the hodographs of these waves on intermediate refracting boundaries, if such boundaries exist, i.e., the determination of the times of arrival of each wave to the points of these boundaries;

c) Construction of the sought refracting boundary itself and determination of the boundary velocity V_b, making use of the isochrones of the time fields for different waves in the medium under the last intermediate refracting boundary.

Construction of the time fields. The time fields for each wave is constructed in the section plane, starting out with the hodograph of this wave, specified on a line of the profile (observed hodograph), or from the hodograph which is transferred to the intermediate refracting boundary. In the case of assumption of a constant velocity V in the medium as a whole, or else constant layer velocities V_i = const, $i = 1, 2, \ldots$, in a stratified covering medium, the construction can be carried out with the aid of a compass. In the case of assumption of variable velocities $V = V(z)$ etc., ray diagrams are used for this purpose.

a) Case of constant layer velocities. The technique of construction of the time fields for constant layer velocities is made clear by the example of Fig. 78.

The hodograph $t(x)$ of a certain wave is specified on the profile x. The velocity in the medium under the lines of the profile is equal to V_1. It is required to construct the time fields for this wave. For this purpose we mark on the profile lines the values of the times t_8, t_9, etc., which correspond to its points. We draw on the hodograph plane an auxiliary line, corresponding to the velocity V_1. The segments r_1, r_2, ... from the time axis to this line are equal to the paths passed by the wave in the medium (V_1) during the time intervals t_1, t_2, ...

We start the construction of isochrones of the time fields, for example, with the isochrone t_9, i.e., we determine the location of the front of the wave at the instant t_9. Obviously, the sought isochrone passes through the point (t_9) of the profile x.

In order for the same wave to reach the point (t_{10}) of the profile, it must consume a time interval $t_{10} - t_9 = t_1$ and pass during this time the path $t_1 V_1 = r_1$. Consequently, the point (t_{10}) of the profile x is located at a distance r_1 from the front of the wave at the instant t_9. We draw a circle of radius r_1 with its center at the point (t_{10}). The isochrone t_9 should be tangent at some point to this circle.

Analogous arguments, advanced with respect to the other points of the profile (t_{11}), (t_{12}), ..., lead to the construction of a series of circles of different radii r_2, r_3, ..., with centers at these points. The sought isochrone t_9 will be the envelope of this family of circles.

This construction represents essentially the application of the well known geometrical Huygens principle, although in a somewhat unusual form: one reproduces the picture of the motion of the front of the wave in space with time t not in the forward direction, but in the opposite direction, in the sequence t_9, t_8, t_7, ...

The construction does not change in principle also in the case of a normal, straight course of time. Thus, the point (t_8) was at the

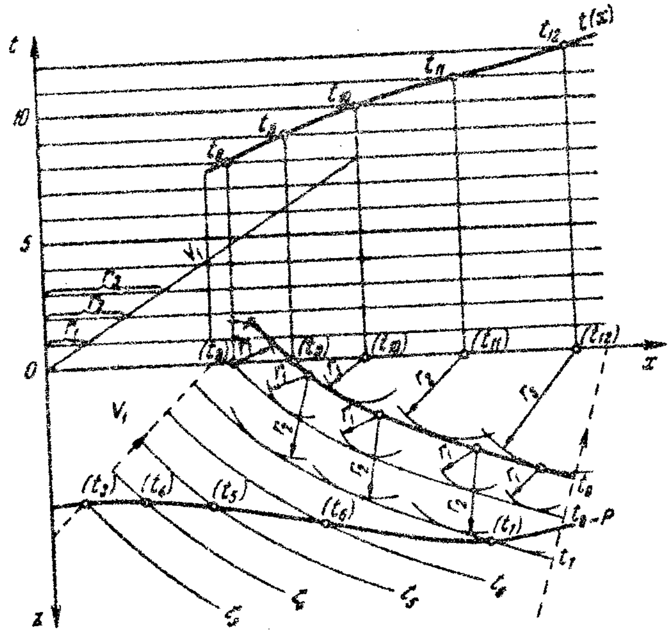

Fig. 78. Construction of isochrones of the time fields on the basis of a specified hodograph t (x) in the case of a constant layer velocity V_1.

instant t_9 already traversed by the wave, and were the velocity in the medium over the line x to remain V_1, then the front of the wave at the instant t_9 would occupy, in accordance to this construction, the position indicated on the diagram near this point.

Thus, the isochrone t_9 has been plotted. The plotting of the remaining isochrones t_8, t_7, ... can be carried out either analogously or simpler, as follows: the obtained isochrone t_9 is taken to be the "reference"; the centers of the circles of equal radii r_1 are placed on it and one constructs, as shown in the diagram (Fig. 78), the isochrone t_8. Then the radius r_2 is taken and the isochrone t_7 is constructed, etc. Thus the entire time field is plotted in the region where the velocity is V_1.

The part of the space where the time fields corresponding to the hodograph t (x) can be determined is bounded by the extreme rays -- rays orthogonal to the isochrones -- as shown on the diagram by the dotted lines.

In practice the method described above of the construction of the isochrones with the aid of a compass can be replaced by the use of templates, on which are drawn mutually parallel lines, corresponding to

the isochrones of a plane wave, propagating with a definite velocity. The isochrones can be constructed also with the aid of a preliminary construction of rays, which are marked suitably with values of time. The angles i between the rays of the vertical upon approaching to the line of the profile x are determined by the well known formula

$$\sin i = \frac{V_1}{V^*}$$

where V* is the apparent velocity on the hodograph t (x) at the corresponding point of the profile.

Now let the line P, shown in Fig. 78, represent an intermediate refracting boundary -- the lower boundary of the layer V_1, under which the velocity in the covering medium will now be different. Then the time field constructed by us has a physical meaning only above this line. The points (t_3), (t_4), ... where the isochrones t_3, t_4, ... intersect the line P determine the hodograph t_d (λ) of the wave under consideration on the intermediate refracting boundary P (the letter λ denotes the distance measured along this boundary from a certain zero point).

If there, a layer with velocity V_2 is located under this boundary P then in order construct the isochrones in this layer of the time field of the same wave, the initial hodograph will be t_d (λ), and the radii of the circles will be determined in accordance with the new value of the velocity (V_2). The method of construction remains the same in all other respects.

Les us proceed to the general case of constructing the time fields in a stratified medium with constant layer of velocities V_i = const at each i-th layer (i = 1, 2, 3, ...).

Let us assume that as a result of the interpretation of the hodographs of reflected or refracted waves, corresponding to the boundaries $P_{1,2}$ $P_{2,3}$, or by other means, we have determined beforehand the structure of the upper layers of the medium: we have constructed all the intermediate boundaries and established the values of their layer velocities. This could be done in practice at least with the aid of the same method which will be described later on. Let us assume furthermore that the layer velocity in the medium underlying the last, lowest intermediate boundary, is known. Then the construction of the time field for the wave arriving from under this boundary and reaching the surface of the earth P_0, where its photograph is observed, reduces to the following operations.

The time field in the lower V_1 in which the velocity is V_1 (Fig. 79) is determined from the given hodograph on the line P_0. This fieldwhere it intersects the boundary $P_{1,2}$, determines the hodograph on this boundary. In time, the hodograph obtained on the boundary $P_{1,2}$ is used for the construction of the time field in the layer V_2, and this field determines the hodograph on the next boundary $P_{2,3}$, etc.

Thus one obtains, finally, the time field in the layer under the last intermediate boundary, which will indeed be used henceforth fo the construction of that (sought) boundary, to which corresponds the hodograph t (x) as specified on P_0.

The region within the boundaries of which is determined the time field, is bounded on the sides, as before, by the extreme rays. In each layer the segments of the rays are constructed as perpendicular to the adjacent isochrones. The result of this construction is identical with that which would be obtained were the rays to be constructed by the angles of incidence and refraction in accordance with the well known sine law.

In the very lowest layer the time field remains unbounded below until the position of the sought refracting boundary is determined. With this, this field is constructed in a somewhat broader region of space in such a way, that the sought boundary is found to be located inside this region.

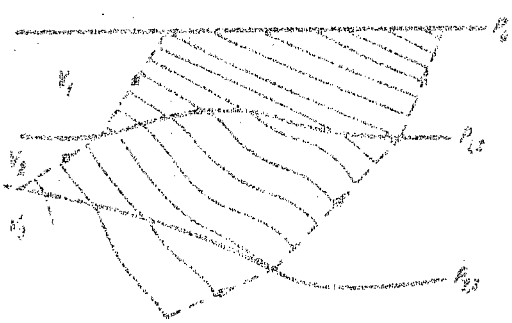

Fig. 79. The time field in a medium with constant layer velocities V_1, V_2, ... The hodograph is specified on the line P_0. This is used to plot the field in the layer V_1; this determines the hodograph on the intermediate boundary $V_{1,2}$; from this one plots the field in the layer V_2, etc.

In practice there is no need for constructing the time field in each layer, including the lowest one, with a large number of isochrones in each region, where these fields can be determined. It is sufficient to construct fully only the separate reference isochrones, and to indicate the remaining ones in the form of small segments of lines only in those places, where it is required for the purposes of the solved problem: in the intersections where the intermediate separation boundaries in order to determine on them the hodographs, and in the direct vicinity of the refracting boundary that is to be constructed, for a detailed determination of its form and the values of the boundary velocity.

b) <u>Case of variable layer velocities</u>. Most frequently it is necessary to use the assumption that the velocity in the covering medium is a function (continuous or piecewise-continuous) of only the depth $V = V(z)$. We shall also consider this case, although construction methods have been developed under more general assumptions [4, 43]. We call attention to the fact that now, in the method of time fields, one has in mind the depth dependence of the layer velocity V, not the average velocity $\bar{V}$, with which we dealt in the approximate methods of interpretation (Section 4).

In order to construct the isochrones of the time field from a given hodograph $t(x)$ in a medium with a variable velocity $V(z)$, use was made of the ordinary ray diagrams on which the rays and isochrones are plotted [14, 58]. Methods of construction are described, for example in the articles [4, 47]. The ray diagram, should, naturally, correspond to that law of velocities $V(z)$, which takes place in the given region. We note that the ray diagram itself represents the time field of straight waves, produced by a point source.

In the case of $V(z)$, just as in the case of $V = \text{const}$, the construction begins with transferring on the profile line the time markers t_{10}, t_{11}, ... from the observed hodograph (Fig. 80). Next one can use two methods for the construction of the isochrones: 1) construct the isochrones as envelopes to determine the elementary fronts; 2) first find the rays and label them with the values of the time.

In the construction by the <u>first method</u>, one first plots the auxiliary elementary fronts with sources at the marked points t_{10}, t_{11}, ... analogous to the circles for the case $V = \text{const}$. They will now be represented by corresponding isochrones of the ray diagram, the origin of which is shifted successively with the labeled points (t_{10}), (t_{11}), ... (Fig. 80).

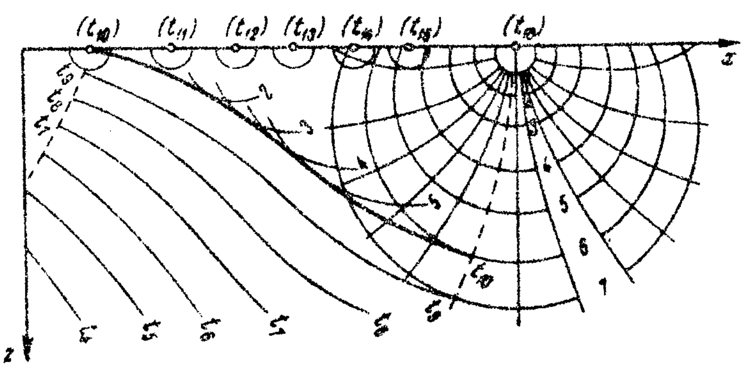

Fig. 80. Construction of the isochrones of the time field with the aid of a ray diagram in the case of a variable layer velocity $V(z)$.

Let us trace, for example, the construction of the isochrone t_{10}. It will pass through the point (t_{10}) of the profile and will be tangent to the elementary front -- the isochrone of the diagram, with a source at (t_{11}), and a time designated on the diagram, the value of which is $t_{11} - t_{10}$. Next, the isochrone t_{10} will be tangent to the elementary front with a source at t_{12} and the time on the diagram $t_{12} - t_{10}$, etc. As a result, the sought isochrone t_{10} is determined as the envelope of all these elementary fronts.

Analogously, we construct also the other isochrones t_9, t_8, ... The region of space, where the time field is determined is bounded, as before, by rays orthogonal to the isochrone, passing in a given case to the points (t_{10}) and (t_{16}) of the profile.

In practice the time field is best constructed on a tracing paper, superposed in a suitable manner on the ray diagram. The technique of construction can be simplified by using previously constructed isochrone template, which represents the time field (isochrones and rays) for a certain specially selected hodograph with a smoothly varying apparent velocity. The construction of the time field on the basis of the observed hodograph with the aid of this template reduces successively transfer directly from this template sufficiently large sections of the time field, which are bounded by the corresponding rays [43].

In the construction of the time fields by the <u>second method</u> one labels the points on the profile line not only with the times t (t_{10}, t_{11}, ...) but also with the apparent velocities V^*, which are measured at the same points from the observed hodograph. Next, rays are drawn through these points, characterized by the corresponding values of the velocities V^*. These are copied from the ray diagram. These rays are labeled with values of the time, using the isochrones of the ray diagram, and then it is necessary to bear in mind that the directions of the increase of time on the diagram and in the sought time field are mutually opposite, and the time labels or the points (t_{10}), (t_{11}), ... of the profile are given. Finally, the equally labeled points of the rays are joined by smooth curves -- the isochrones of the time field, which we have constructed.

<u>Construction of sections</u>. The methods of construction of refracting boundaries and determination of the boundary velocities by the method of time fields remain the same in principle, independent of what the distribution of the layer velocities in the covering medium may be: whether it is assumed that this medium is homogeneous, $V = \text{const}$, or whether it is stratified with jump-like changes in the velocity V_1, V_2, ... on the intermediate refracting boundaries, or else it is assumed that the layer velocity varies continuously as a function of the depth $V = V(z)$, etc. Therefore we shall henceforth speak only of different problems of interpretation of hodographs -- individual, opposite, or overtaking, which will be solved for any assumption regarding the behavior of the layer velocities.

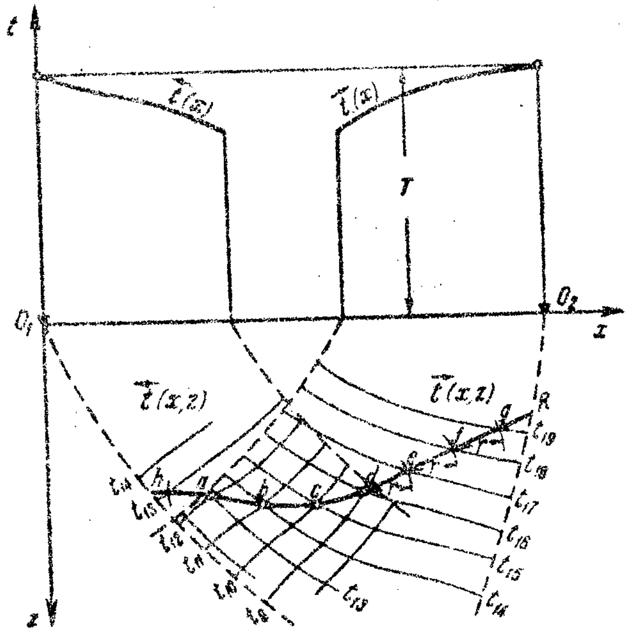

Fig. 81. Construction of the refracting boundary R on the basis of opposing hodographs $\vec{t}(x)$ and $\overleftarrow{t}(x)$. The points a, b, c, d of the boundary R are determined by the intersection of these isochrones of the opposite time fields, the sum of labels of which is equal to the time T at the mutual points. In this case it is assumed $T = t_{25}$.

a) Interpretation of the opposing hodographs. In this case we shall assume that the wave in the medium under the sought refracting boundary glides along this boundary. The interpretation will consist of the following: 1) determination of the position of the boundary and 2) determination of the boundary velocity.

From the given hodographs, the direct one $\vec{t}(x)$ and the reverse one $\overleftarrow{t}(x)$, we plot the corresponding opposing time fields $\vec{t}(x, z)$ and $\overleftarrow{t}(x, z)$ (Fig. 81).

1) The points of the refracting boundary R are determined by the equation

$$\vec{t}(x, z) + \overleftarrow{t}(x, z) = T, \tag{23}$$

where T is the time at the mutual points, measured by the hodographs. In other words, the refracting boundary is determined by the points of intersection of those isochrones of opposing time fields, the sum of labels of which is equal to the time at the mutual points.

Thus, if on Fig. 81 the time is $T = t_{25}$, then the point a of the refracting boundary, lying on the isochrone t_{12} of the time field $\overrightarrow{t}(x, z)$, is found on the intersection of this isochrone with the isochrone $t_{25} - t_{13} = t_{12}$ of the other time field $\overleftarrow{t}(x, z)$. Analogously, the point b is determined by the intersection of the isochrones t_{11} and t_{14}, the point c -- by the intersection of the isochrones t_{10} and t_{15}, etc.

It is seen from Fig. 81 that to determine the boundary it is enough to find, by use of Eq. (23), only one point; the remaining points of the boundary are determined by drawing diagonals of the elementary rhombi formed by the isochrones of the opposing time fields.

The boundary is determined in this way in the region of space, where both time fields are known (points a, b, c, and d of the boundary on Fig. 81). We shall deal separately with prolonging it outside this region (points e, f, g, and h of the boundary), when discussing methods of interpretation of individual hodographs.

We note that if the time T at the mutual points is unknown -- when not one of the opposing hodographs reaches the mutual point, -- then it is possible to determine a family of curves, which represent the possible positions of the refracting boundaries. Segments of these curves are determined by the diagonal elements of the rhombi, formed by the isochrones. These curves will frequently retain approximately the same form, but are located at different depths.

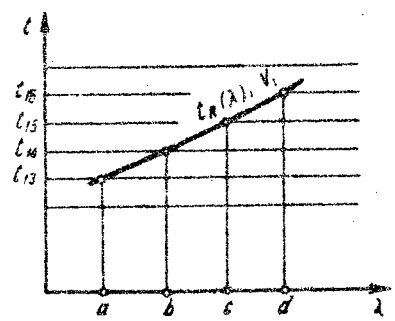

Fig. 82. Hodograph of a gliding wave along the boundary R, shown in Fig. 81. The boundary velocity V_b equals the apparent velocity determined by this hodograph.

2) To determine the boundary velocity V_b one plots the hodograph $t_R(\lambda)$ of the wave gliding along the obtained refracting boundary R (Fig. 82). The abscissas of this graph represent the distances λ measured along the curve R from a certain point of the curve, taken as the zero point; the ordinates represent the times at the points a, b, c, ... of the boundary, read from the isochrones of one of the time fields, for example the field $\bar{t}(x, z)$ with which this boundary was constructed.

The boundary velocity V_b at the points of the boundary R is equal to the apparent velocity in the corresponding points of the hodograph $t_R(\lambda)$ of the gliding wave.

In practice the hodograph $t_R(\lambda)$ of the gliding wave is drawn through the point with a certain averaging of the law that describes their positions, assuming that the individual points deviate within the limits of possible observation and plotting errors. Usually this hodograph is represented in the form of a broken line, if possible with a minimum number of breaks. The straight-line segments of this hodograph give the values of the boundary velocity V_b on individual sections of the refracting boundary.

b) <u>Possibilities of interpretation of an individual hodograph of refracted waves.</u> If there is available only one hodograph t (x) of refracted waves and the position of its initial point IP (Fig. 83) is known, and if furthermore, as always, the velocity V_1 in the covering medium is known, then these data are sufficient in principle to construct the refracting boundary R and to determine the boundary Velocity V_b under the assumption that this velocity is constant; in this case the wave in the refracting layer assumed to glide along the boundary ([53], p 83).

However, more frequently it happens that the position of the initial point of the hodograph t (x) remains unknown. Then the refracting boundary can be found with one hodograph t (x) only under the condition that the boundary velocity V_b is also specified. It is assumed with this that the hodograph t (x) can be extended over a sufficiently close distance to its point of explosion.

Let us assume that the initial point of the hodograph t (x) is unknown and the value of V_b is not specified. In this case it is possible to determine the curve S of the possible points of entry of the seismic radiations, representing the geometric locus of the positions of the point A, where the direct wave is incident on the refracting boundary R at a critical angle i ($\sin i = V/V_b$) for all possible values of the boundary velocity V_b (Fig. 83). This curve S will be the envelope of the family of refracting boundaries R, corresponding to one and the same hodograph t (x). The parameter of this family is the quantity V_b.

The curve S is constructed on the basis of the specified hodograph t (x) in accordance with the rules of construction of a <u>reflecting</u> boundary, i.e., formally the same way as if the hodograph t (x) were to correspond to a wave not refracted by the boundary R, but reflected by the boundary S.

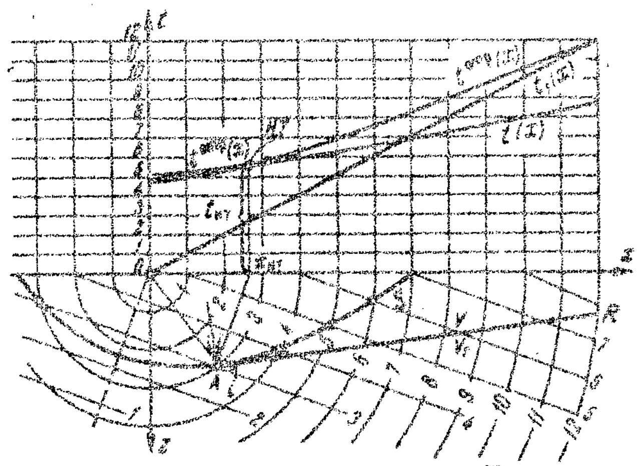

Fig. 83. For use in finding the possible solutions of the problem of a single hodograph t (x) of refracted waves, when its initial is not determined and the boundary velocity V_0 is not specified.

In fact, if one assigns to the value V_b the successive different values, then this corresponds to shifting the initial point along the curve t (x). On the other hand, in the initial point, as is known, the element of the hodograph of the refracted wave coincides with the element of the hodograph $t^{refl.}$ (x) of the wave reflected from the section of the boundary at the point A (Fig. 83). Taking all the points of the hodograph t (x) as initial points, successively one after the other, we identify these points with the points of a certain hodograph of reflected waves. The reflecting boundary for this hodograph is the geometric locus S of the points A at different values of V_b.

In order to obtain the curve S it is possible to employ any method of constructing reflected boundaries, known in the reflected-wave method, for example, the intersections, ellipses, etc., provided the law assumed for the velocities, V = V (x, z), admits of its use. When the constructions are carried out with the aid of the method of time fields, the curve S is determined by the points of intersection of equally-marked isochrones of two time fields: for the incident wave (with the source at the point of explosion (O) and for the "reflected" wave, the hodograph t (x) of which is specified.

In the case V = const, the isochrones of the time field of the incident wave represents concentric circles with a center O (Fig. 83). If $V = V(z)$, on the other hand, this field coincides essentially with that shown on the corresponding ray diagram, which in turn must be placed with its origin at the point E. The time field for the "reflected " wave coincides in this case with the time field of the refracted wave, which is determined by the hodograph t (x) in the usual manner.

We note that the point where the curve S intersects the x axis coincides with that point of the profile, which corresponds to the intersection of the hodographs of the direct wave t_1 (x) and the refracted wave t (x). In the case of a straight-line hodograph t (x) and a constant velocity V, the curve S is a parabola whose axis is perpendicular to the isochrones of the time field of the refracted waves in the covering medium (V).

The practical meaning of the construction of the curves S may consist of the fact that they make it possible to separate the regions around the points of explosion, to which the refracting boundary R should not enter. By specifying some value of V_b it would be possible in the future to construct different versions of positions of the boundary R, which will be represented in the form of curves which are tangent on the outside to the curve S. If there are several points of explosions and each of these has its own curve S, then the refracting boundary can be drawn as the envelope of all the curves S.

However, the principal purpose of the curves S is for use in the interpretation of overtaking hodographs of refracted waves with the determination of the boundary R and of the value of the boundary velocity V_b with the aid of these hodographs (see later, p 154 /of source/).

c) Construction of the boundary on the basis of an individual hodograph in the case of gliding. The case when the wave in the layer under the refracting boundary can be considered as a gliding wave, is encountered in practice most frequently.

For the construction of a unique fully defined refracting boundary R from one hodograph (with unknown initial point) it is necessary, as we have seen, to determine beforehand the boundary velocity V_b. This can be done, for example, by interpretation of opposite hodographs, obtained on the neighboring section of the profile.

Different versions are possible in the problem of the total interpretation of an individual hodograph. Most frequently, however, one encounters the following question: the refracting boundary R is defined over a certain section of the profile on the basis of opposite hodographs $\overrightarrow{t}(x)$ and $\overleftarrow{t}(x)$ of refracted waves (points a, b, c, d of the boundary R on Fig. 81). It is required to complete this boundary, by determining its position in that region of space, where there is a time field, constructed only on the basis of an individual hodograph $\overrightarrow{t}(x)$ (or $\overleftarrow{t}(x)$).

The problem is solved in the following manner. Taking as the initial known point a certain known point d of the refracting bound;ary (Fig. 82), one draws with this point as a center an arc of a circle of

of radius $r = V_b \Delta t$, where Δt is the difference in times between neighboring isochrones. The point e where this circle intersects the neighboring isochrone represents one of the points of the unknown refracting boundary R. Next, one places the center of the circle at the point e and analogously, by intersection, one finds the next point f of the boundary R, etc.

In Fig. 81, on the left of the previously determined point a of the boundary R, is shown an analogous construction of the point h of this boundary, on the basis of a single time field, obtained from the other hodograph $\overleftarrow{t}(x)$.

In order to make the intersections with a compass, it is convenient to mark a rule made of a bent strip of paper in segments of arc, by plotting on it previously calculated length r, 2r, 3r, etc. When constructing the boundary on the section e, f, g, one of the markers of the rule is made to coincide with the point d, and the others are made to coincide successively with the corresponding isochrones of the field $t(x, z)$, and the rule, where necessary, is turned slightly in a suitable manner. This method eliminates to a great extent the possibility of accumulating an error in the determination of the position of the boundary R on the basis of a single hodograph, an error due to multiple successive intersections by means of a compass, which is difficult to set with sufficient accuracy to a small radius r.

d) Construction of a boundary from an individual hodograph in the case of penetration. If there are gounds for assuming, for example, on the basis of the non-parallelness of the overtaking hodographs, that the wave in the medium under the refracting boundary does not glide along it, but penetrates inside the layer, then under certain conditions it is possible to construct the refracting boundary on the basis of a single hodograph with full allowance for this penetration. For this purpose it is necessary to know beforehand the value of the velocity V_2 in the layer below the boundary.

One of the possible versions of the problem of the penetration is shown in Fig. 84. It is assumed here that the hodograph $t(x)$ is specified; the value of the velocity $V_1 = V_1(x, z)$, in the covering medium is known, and in addition, the position of one point S, lying on the refracting boundary R, is also specified. It is required to determine the position of the remaining points of this boundary, assuming that the point S can be considered as an intermediate source of waves in the underlying layer.

The problem is solved in the following manner: the specified hodograph $t(x)$ is used to plot a time field $t(x, z)$ in the medium with velocity V_1 (Fig. 84). This determines the time at the point S, in this case t_{10}. Next, using the point S as the center, circles are drawn -- isochrones of the wave in the layer under the boundary. Their radii are equal to $r_1 = V_2(t_{11} - t_{10})$, $r_2 = V_2(t_{12} - t_{10})$, etc. The refracting boundary represents the geometric locus of the points of intersection of the isochrones of two time fields in the media above and below the boundary. In other words, its points are determined by

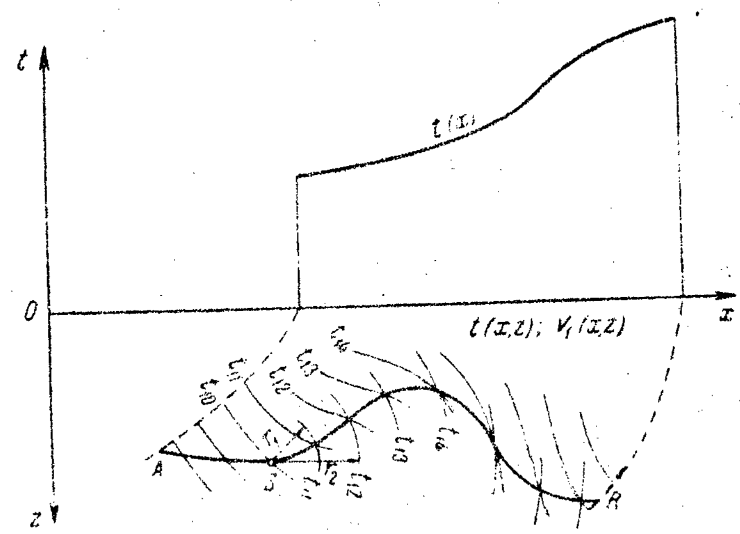

Fig. 84. Construction of the refracting boundary R in the case of penetration of a wave within the layer, lying under this boundary. The point S is a specified point on the boundary R, which can be assumed to be as an intermediate "source" of a wave (circles with radii r_1, r_2, ...). The remaining points of the boundary S are determined by intersection of isochrones of equal labels.

the intersection of identical isochrones of these two fields of time. At the same time, one of the points of the boundary is determined by the point of intersection of this circle of radius r_1 with the isochrone t_{11} of the time field in the covering medium; the second point -- by the intersection of the circle with radius r_2 with the isochrone t_{12}, etc. By joining these points with a smooth curve, we plot the entire sought boundary R.

In Fig. 84 the boundary is essentially convex upward, and in this case the assumption of penetration is quite natural. But the boundary may assume at certain sections such a form -- for example, a strong convexity downward -- that the assumption of penetration loses its physical meaning. Such sections of the boundary must be constructed in accordance with the preceding method, for the case of gliding.

In other versions of the problem of the interpretation of a single hodograph it can be assumed in the case of penetration that the isochrones of the wave in the layer under the refracting boundary R are not circular, as shown in Fig. 84, but represent a sequence of mutually-parallel straight lines, normal to the specified section AS of the boundary R,

or else that these lines represent the result of the intersection between the plane of the drawing xz and cylindrical surfaces with a vertical axis z passing through the point of explosion O. The choice of either variant is determined by the prevailing conditions: the data on the boundary R, where its position is known, the form of the specified hodograph t (x), the resultant form of the boundary R after it is constructed, etc.

e) Interpretation of overtaking hodographs. Assume that there are available overtaking hodographs $\overrightarrow{t_1}$ (x) and $\overleftarrow{t_2}$(x), which can be prolonged sufficiently towards the points of explosion O_1 and O_2 (fig. 85). In order to insure such a possibility for the hodograph $\overrightarrow{t_1}$ (x), it may be necessary to have an additional overtaking hodograph $\overrightarrow{t_0}$ (x).

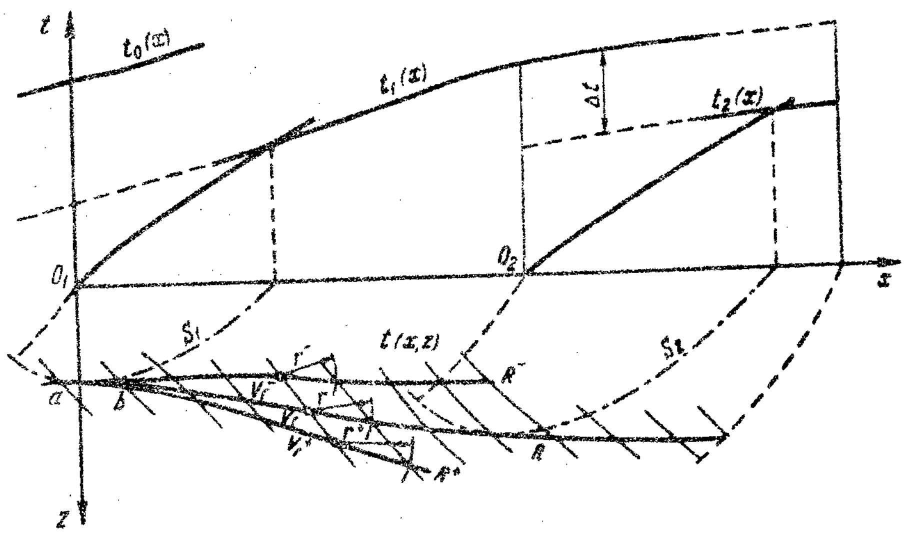

Fig. 85. Construction of the boundary R and determination of the boundary velocity V_b (const) on the basis of overtaking hodographs of refracted waves. The sought boundary R is tangent to the curves S_1 and S_2 of the possible points of entry of the seismic radiations.

Let us assume that it is possible to consider the wave in the layer under the sought boundary R to be gliding. The problem consists of constructing the boundary R and determining the corresponding boundary velocity V_b under the assumption that this quantity is constant on the profile between O_1 and O_2.

For the solution, we plot the time field t (x, z) from the summary hodograph, reduced to any explosion point, for example, O_1; then this will be the hodograph $\overset{*}{t}_1$ (x), prolonged suitably with the aid of o er hodographs.

We then plot two auxiliary curves S_1 and S_2 of the possible points of entry of the seismic radiations (see p 151 [of source]) for the hodographs $\overset{*}{t}_1$ (x) and $\overset{*}{t}_2$ (x) with explosion points O_1 and O_2. If these curves, which represent, as is known, formerly "reflecting boundaries" are constructed by the method of time fields, then the curve S_1 is constructed, as usual, by the points of intersection of equally-marked isochrones of two time fields: the field t (x, z) and the time field of the direct wave with source at point O_1. In the construction of curve S_2, on the other hand, in view of the shift of the hodograph t_2 (x)*, it is necessary to take this transfer operation into account and to find the points of intersection of the isochrones of the field t (x, z) with the isochrones of the field of the direct wave with source at O_2, the times on which should be increased by the same amount Δt.

The next step is to construct the sought boundary with simultaneous determination of the boundary velocity. This is convenient to do in the following manner. By placing a rule tangent to both curves S_1 and S_2, one first finds the approximate value of V_b by dividing the distance along the rule between the points of intersection with any two isochrons of the field t (x, z) (it is better if these are sufficiently removed from each other) by the time difference between these isochrones. This position of the rule will represent the approximate position of the sought boundary R under the assumption that it is linear.

The result obtained is then refined, by plotting the boundary R for different values of V_b (=const), close to that found approximately, by the method already described for the case of a single hodograph in the presence of gliding (p 152 [of source]). With this, instead of the initial point, analogous to the point d on Fig. 81, the initial point in this construction will be the initial element of the boundary of length $r = V_b \Delta t$ (where Δt is the time difference between the neighboring isochrones), which fits between the isochrones of the field t (x, z) along the tangent to the curve S (segment ab on Fig. 85). The construction of the boundary can be carried out by intersecting the isochrones with arcs of circles of radius r with successive transfer of the center at the points of intersection.

If it is found that as a result of the construction the boundary R will be located higher than necessary (the curve R^- on Fig. 85, constructed by means of intersection with the radius r^-), then the assumed value of V_b ~~XXXXXXXXXXXXXXXXXXXX~~ must be increased, and if it is below (curve R^+ ON The same diagram, constructed by the intersections with r^+), it should be decreased. The true value of V_b will be that for which the boundary R will pass tangent to the curve S_2. This value of V_b in the corresponding position of the boundary R is indeed the result of the solution of this problem.

*by a time interval Δt when it is reduced to the summary hodograph $\overset{*}{t}_1$ (x), it is necessary ...

As in the case of an individual hodograph, it is more convenient and more accurate in practice to construct the boundary by overtaking hodographs not with the aid of a compass, but by using a paper rule marked in intervals of r (p 152 /of source/).

6. Interpretation of Hodographs in the Case of a Step

The refracting boundary may be of the form of a step ABCD (Fig. 86), owing to a discontinuity and a vertical shift (fault), or a steep local imbedding of the refracting layer (monoclinal folding) or else because of erosion.

Fig. 86 shows hodographs for these same two cases of a step, as in Chapter IV, Section 10: a) when the waves penetrate within the second layer (see rays A'C or CC'); here it is necessary to assume that the thickness of the refracting layer (with velocity V_2) exceeds the height Δh of the step, and b) when the waves in the refracting layers are only gliding; it is then assumed that AB and CD are thin layers (with velocity $V_b = V_2$), which bound above and below with the medium characterized by velocity V_1; in this case the trajectory of the ray has, for example, the form ABED.

On the diagram it is assumed for simplicity that the velocities in the layers V_1 and V_2 ($= V_b$) are constant, and that the sections AB and CD of the boundary are straight lines and horizontal, and the drop BC in the step is vertical. These conditions will be assumed at first as specified in the discussion of this problem, but later on we shall indicate also those methods of interpretation, which make it possible to become free to a greater or lesser extent of such limiting conditions.

The meaning of the principal hodographs, shown in Fig. 86, and the dynamic features of the corresponding waves were clafified in Chapter IV, Section 10 (see also Fig. 68).

The interpretation of the hodographs in the case of a step consists essentially of establishing the place of the step in plan (x_B) and of determining its height Δh. The depth H of the boundary AB in the raised portion will be considered either known or, in the other case, also to be determined; the same concerns also the velocity V_2 ($=V_b$). The velocity V_1 is assumed specified. The values of H, V_1, and V_2 can be determined by means of the known methods at least as a result of interpretation of systems of hodographs with explosion points located above the raised portion of the boundary (in the case of velocities also above the dropped one), where it does not have any discontinuities. We note also that the velocity V_1, used to determine the height Δh of the step, is the layer velocity at that depth where the step BC is located (Fig. 86). On the other hand, in the determination of the depth H, at which the upper edge B of the step is located, the quantity V_1 must be taken to mean the velocity which characterizes the medium covering the boundary AB. Let us consider two methods of

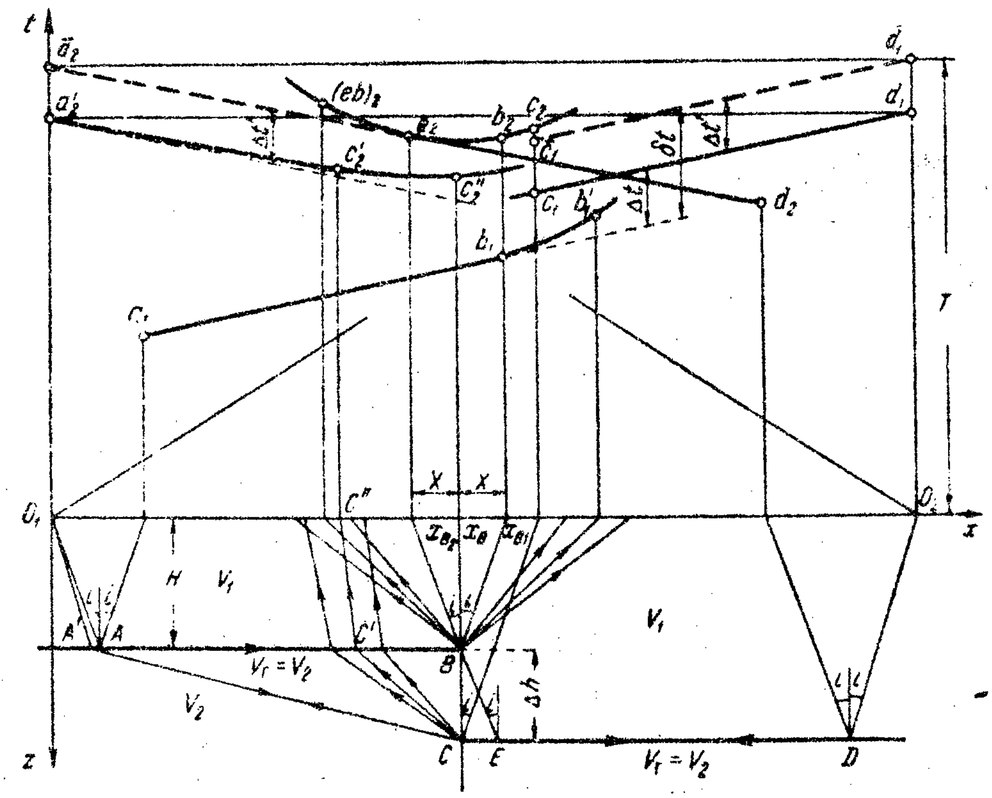

Fig. 86. Interpretation of longitudinal hodographs in the case of a step. The points of the hodographs connected with definite points of the refracting boundary are denoted by identical letters, but on the boundary with capital letters and on the hodographs with lower case letters. The indices 1 and 2 correspond to the numbers of the points of explosion O_1 and O_2. The hodographs in the case of gliding (trajectory O_1ABEDO_2) -- $\bar{a}_1b_1b_1'$; $\bar{c}_1\bar{d}_1$; $d_2e_2\bar{a}_2$; the hodographs in the case of penetration (trajectory $O_1A'CDO_2$) -- $a_1b_1b_1'$; c_1d_1; $c_2''c_2'a_2'$.

<u>Analytical methods</u> consist of employing simple formulas, which are partially based (in the determination of Δh for the case of penetration) on approximate assumptions.

a) **Determination of the position of the step in plan.** The horizontal coordinate x_B of the point B of the step -- its diffracting edge -- can be obtained by means of several methods, using the dynamic features of waves on the records on the seismograms and particularly the shapes of the hodographs.

Usually the most reliable to establish is the coordinate x_{B1} of the point b_1 of the direct hodograph (with point of explosion O_1) where the frontal refracted wave (its hodograph a_1b_1) is replaced by the diffracted wave ($b_1b'_1$).

The section x_B, x_{B1} (seismic drift) is equal to

$$X = Htgi, \tag{24}$$

where $\sin i = V_1/V_2$. Laying off the segment X from the known point x_{B1} along the direction towards O_1, we find the sought point x_B.

An analogous construction can be made by using the point e_2 of the inverse hodograph d_2e_2 $(eb)_2$ (with explosion point O), where the frontal wave d_2e_2 is replaced by a diffracted wave e_2 $(eb)_2$, which bends around the edge B of the step on the outside, which propagates in the medium with velocity V_1.

Making use of the peculiarities of the shape of certain branches of the hodographs, it is possible sometimes to establish the position of the point also in the case of unknown value of H. Thus, at the point x_B is located the minimum of the curved hodograph $(eb)_2e_2b_2$, corresponding to a series of waves of diffracted type. Adjacent to this hodograph is a short straight-line segment b_2c_2, due to reflection from the rise BC of the step of the frontal wave, produced in the section EC of the dropped portion of the boundary.

At the same point x_B is located also the minimum, c_2'' of the second hodograph $c_2''c_2'a_2$ (with the same point of explosion O_2), which corresponds on the left to this point to the wave propagating along paths of the type $O_2DCC'C''$, i.e., which is connected with the raised portion of the boundary. The region of the minimum of this hodograph, however, is broader than that of the preceding one, and it extends to the left of x_B over a greater section of the profile than to the right of this point; in addition, the corresponding waves are usually characterized in this region by a small amplitude; all this makes it difficult to use the given hodograph for a sufficiently reliable fixing of the position of the point x_B.

Both of these curved hodographs are asymmetrical with respect to the time axis, passing through the point x_B. But among the branches of the direct and inverse hodographs there are two branches, which make it possible to compile one symmetrical curve. This is the bent branch $b_1b'_1$ of the direct hodograph and the bent branch e_2 $(eb)_2$ of the inverse hodograph. Both these branches have a mirror symmetry with respect to the time axis passing through x_B, but are replaced with a shift along this axis. They are best made up by eliminating this shift by transferring one of these parallel to the axis, for this

purpose one can copy one of the branches on tracing paper. After making up in this manner one common symmetrical curve, it is possible to obtain its symmetry axis and as a result to determine x_B.

We note also that the form of this curve as a whole, or else of its component parts, makes it possible to determine the depth H of the edge B of the step under the point x_B of the profile, as will be discussed later (p 159 [of source]); the sum curve makes it possible in principle to determine the value of V_1 under the condition V_1 = const.

b) Determination of the height of the ledge of the step. To determine the height Δh of the ledge of the step, use is made of the value of the "jump" of the direct (Δt or δt) or reverse ($\Delta t'$) hodograph upon passing through the place of the step. The jump is determined by the distance in time between approximately parallel broken branches of any one hodograph.

In the case of penetration (here it is the more frequent case) for a step of "small" height Δh use is made of the following approximate formula (Fig. 86):

$$\Delta h = \frac{V_1 \Delta t}{\cos i} \qquad (25)$$

where $\sin i = V_1/V_2$. This formula is applicable both to the direct and to the reverse hodograph, inasmuch (in the case of a step of small altitude) the jumps Δt and $\Delta t'$ of both hodographs are approximately equal: $\Delta t' = \Delta t$.

The approximateness of these relations is due to the fact that in the derivation of formula (25) it is assumed (see for example [14] part 2, p 32) that the time of travel of the wave from the point of explosion to the points B and C (or for the explosion in O_2 in the inverse direction) is the same. This is approximately true if BC $\ll$ AB. The "smallness" of the height Δh should also be understood in this sense.*

From an examination of the form and placement of the branches of the hodographs (Fig. 86) it follows that the magnitude of the jump can be determined in practice more accurately with the straight hodograph, than with the inverse. The branch $c_2''c_2'a_2'$ of the reverse hodograph, corresponding to the raised portion of the boundary, approaches slowly asymptotically the straight line parallel to the branch d_2e_2 for the dropped portion, so that the distance $\Delta t'$ ($\approx \Delta t$) between these parallel straight lines is difficult to read.

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* A fully analogous assumption serves as the basis of the calculation of the depth of refracting boundaries by means of non-longitudinal hodographs of refracted waves by the method of the "horizontally-stepped boundary" (Chapter VI). This explains why the principal formulas are identical.

In the case of gliding, when it is assumed that a thin layer with valocity $V_b = V_2$ is underlined by a medium with a velocity V_1, the reverse hodograph represents a straight line d_2a_2 (Chapter IV, Section 10), and does not make it impossible to determine the height of the step. On the other hand the branches of the direct hodograph: a_1b_1 and c_1d_1 form a jump of magnitude $\delta t = 2\Delta t$. In view of this, formula (25) is replaced in this case by the following formula.

$$\Delta h = \frac{V_1 \delta t}{2\cos i}. \tag{26}$$

This formula remains valid (but only in the case of gliding!) and at a large height Δh of the step.

We note that only one hodograph with an explosion point above the raised portion of the step does not make it possible to judge the particular case with which we deal -- penetration or gliding -- and correspondingly does not tell us which of the formulas -- (25) or (26) -- should be used. This question can be solved only by obtaining a second hodograph, with a point of explosion above the dropped portion of the step.

If the height of the step in the case of penetration cannot be considered small, then its determination can be carried out by means of successive approximation in the following manner: first one finds the value of Δh by means of formula (25) and the section is constructed. Then, considering this section to be known, the times of travel of the waves along a path of type $O_1A'CDO_2$ is determined, and the difference between the times calculated in this manner and the times measured by the hodograph is found. After inserting this difference in place of Δt in the same formula (25), we obtain instead of Δh the correction that must be introduced in the previously obtained value of Δh, etc. Usually the first correction of the section is sufficient to obtain good agreement between the time calculated by its means and the measured time.

The value of Δh of the step can also be calculated with allowance for the variation of the velocity with depth z, using for this purpose the average velocities $\bar{V} = \bar{V}(z)$, as is done in the interpretation of non-longitudinal hodographs of refracted waves (Chapter VI, Section 4).

The described analytic method of determining Δh can be used also in the case of inclined (but mutually parallel) parts of a refracting boundary AB and CD. In this case Δh is the height of the step along the normal to AB and CD. The initial assumption will be that the times of arrival of the wave from O_1 to the points BC, which are located on the same normal to the boundary, are equal ([14], part 2, page 32).

The most important condition of applicability of this method is the approximate linearity and mutual parallelness of the branches of the hodographs before and after the discontinuity, which is possible if the separated parts of the boundary are approximately linear and are mutual parallel, and also if the velocities V_2 $(= V_b)$ remain constant, particularly on the sections before and after the

drop of the boundary.

Constructions by the time-field method. Using the method of time fields, it is possible to become rid to a considerable extent of the limitations indicated above. Thus, the velocity V_1 can be both constant and variable; the boundary on both sections can be curved; the boundary velocities on these sections need not be the same. The assumption of the smallness of the height of the step also drops out. It is possible, also, not to assume that the upper edge B and the lower edge C of the step lie on one vertical one or on one line normal to the boundaries.

Nevertheless, for the sake of simplicity in the argument, we shall carry out the derivation of the assumption that the velocities V_1 and V_2 ($=V_b$) remain constant. If this is not so, it will be specially mentioned.

a) Determination of the position of the upper edge of the step. For this purpose it is possible to use the hodographs Bb_1b_1' or $e_2(eb)_2$ of the waves diffracted with respect to the edge B of the step (Fig. 86). The time field, constructed by the known method (page 144 [of source]) from either of these hodographs, is represented by concentric circular (if $V_1=$const) isochrones, the center of which determines the position of the sought point B. This will also determine its depth H under the surface of the earth.

b) Construction of the raised and lowered parts of the boundary. Such a construction can be carried out primarily by means of single hodographs, with points of explosion over the corresponding parts of the boundary. Thus, to determine the boundary on the section AB it is necessary to use the hodograph a_1b_1, while on the section AD one used the hodograph e_2d_2.

More accurately speaking, to solve this problem under the assumption that the initial points and d_1 and d_2 of the hodographs are unknown and the boundary velocity V_b V_2 is not specified, it is necessary to make use, in addition, of overtaking hodographs (not shown in Fig. 86). Their points of explosion should be located at greater distances from the step than the points O_1 and O_2. Each pair of overtaking hodographs is interpreted in the usual manner (page 154 [of source]).

If the velocity V_b is a specified constant quantity, and the point B (the supper edge) is determined beforehand, then the construction of the boundary on the raised section AB can be carried out on the basis of a single hodograph a_1b_1 without making use of the overtaking hodograph, using the method of interpretation of individual hodographs (page 152 [of source]). The difference between the present case and that discussed in page 152 [of source] will consist only of the fact that it now becomes necessary to make known intersections, starting with the point B (Fig. 86), which is more remote from the point of explosion, then the points of the boundary which are to be determined, whereas construction previously was carried out in the opposite direction.

Assuming that the velocity V_b is specified, it is possible to construct the boundary also on the dropped portion, using only the straight hodograph a_1b_1, c_1d_1. In this case the penetration is taken into account as indicated in page 153 [of source]). By way of an "intermediate source of oscillations" for the construction of the known concentric circles, which represent approximately the isochrones of the time field in the layer with velocity V_2, it is possible to choose the point A (Fig. 86). If the boundary AB in the region of the point of explosion O_1 has been determined previously, then this time field can be constructed also by the exact method, following the general rules: first construct isochrones of the time field, with source O_1 in the ocovering medium (at V_1= const these will be circles with center at O_2); this determines the hodograph on the boundary AB. On the basis of this hodograph one constructs the time field in the layer with velocity V_2.

The start of the boundary CD (point C) is constructed on the basis of the points of intersection of equally-labelled isochornes of the two time fields: the indicated field in the layer V_2, and the time field of the frontal wave in the layer V_1, which is constructed on the basis of the hodograph c_1d_1.n The continuation of the boundary CD towards the points D can be obtained under the assumption that the wave glides along the section CD, whereas the point C will serve as the initial point for the drawing of the known intersections.

Analogous construction of both parts of the boundary -- not only the dropped one, but also the raised ones -- on the basis of the hodographs d_2e_2 and $c_2''c_2'a_2'$ with a point of explosion at O_2, can be realized if one can determine the position of the point C, a subject which will be discussed somewhat later. If the position of the point C and the time when the wave arrives at this point from O_2 are known, then the boundary AB can be constructed from the hodographs $c_2''c_2'a_2'$ by means of the ordinary rules of interpretation of individual hodographs in the case of penetration, and the intermediate source of socillations will be the point C.

Let us turn now to the possibility of simultaneous processing of the branches of opposite hodographs above the dropped portion of the boundary. This is of particular importance for the greatest accuracy of determination of its general inclination, and also the value of the boundary velocity, since the interpretation of individual or overtaking hodographs is less reliable in the furthest purpose.

In the case of gliding (for steps this is the less frequent case) the problem of simultaneous interpretation of opposing branches of hodographs c_1d_1 and d_2e_2 is solved in exactly the same way, as in the absence of a step (page 149 [of source]: the position of the boundary ED is determined by the points of intersection of those isochrones of two known fields of times, the sum of designations of which is equal to the time T at themutual points. The

velocity V_b is determined by the hodograph of the gliding wave, whereas this velocity can also be variable.

In the case of penetration, the time at the mutual points cannot be used directly for this purpose. To obtain in this case an approximate solution -- for small Δh -- the problem can be reduced to the previous problem by shifting the hodograph c_1d_1 parallel to the time axis upward by a segment Δt, equal to the jump of the direct hodograph. On the other hand, the exact solution for any Δh can be obtained in the following manner. The time fields, constructed on the basis of the opposing hodographs c_1d_1 and d_2e_2, are used to find a series (family) of curves, which represent the possible positions of the boundary ED. The paramter of the family will be a quantity T. The constructions are carried out for each fixed value of T in accordance with the general rules. For each curve of the family it is possible to determine, as before, the boundary velocity V_b. Strictly speaking, the values of V_b for different curves are in general different, but in practice they usually depend little on which of the curves is used for this determination.

The problem will next consist of choosing, from the obtained family of curves, that particular curve which will give, for a trajectory of the type $O_1A'CDO_2$, a travel time equal to that measured by the hodograph. For this purpose it is possible to use the time field of the waves propagating along the trajectory of this type, constructing it either by the exact method or else approximately, taking the point A as the intermediate source, as indicated above.

Other versions of the solution of this problem are also possible.

We now consider the possibility of simultaneous processing of the branches of opposing hodographs above the raised portion of the boundary. In the case of gliding the opposing branches a_1b_1 and e_2a_2 make it possible to determine the position of the boundary on the section AB with the aid of the cordinary constructions (page 149 [of source]) if one assumes as the time at the mutual points the quantity $(T - \delta t)$, wh re δt is the magnitude of the jump of the direct hodograph. The boundary velocity in the section AB is also determined in the usual manner, and its values will depend little on the quantity δt, which can be determined not fully reliably.

However, in the case of penetration a direct simultaneous processing of the opposing branches a_1b_1 and $c_2''c_2a_2'$ is impossible, in view of the fact that the second branch $(c_2''c_2a_2')$, connected with the penetration, cannot be used under ordinary constructions, which are true only in the case of gliding.

<u>c) Determination of the position of the ledge and the lower edge of the step.</u> This is the most difficult part of the problem, since the recordings of the waves with these elements of the step are frequently difficult to separate on the seismographs.

The construction of the lower edge (point C) can be carried

out in principle by using the hodograph $a_2'c_2'c_2''$, or more accurately that portion of this hodograph, which still deviates noticeably from the asymptotes shown dotted in Fig. 86. The time field constructed by this hodograph in a double-layer medium with velocities V_1 and V_2, taken into account refraction on the previously constructed boundary AB, is represented in the layer V_2 (= const) by concentric circular isochrones, whose center indeed determines the sought point C.

The present construction determines at the same time also the time of arrival to this point of the wave along the path O_2DC. This makes it possible to use it for control or refinement of the position of the boundary on the dropped portion CD.

Points B and C, when considered simultaneously, determine the general direction of the ledge BC of the step. The position of the step can be determined in principle also by the hodograph of the wave reflected from BC, which propagates along trajectories of the type O_2DEEx_{b1}. The reflecting boundary BC is determined by the points of intersection of equally-named isochrones of the following two time fields: the field of the reflected wave (which is constructed on the basis of the hodograph b_2c_2) and the field of the frontal wave, connected with the point DE for an explosion at the point O_2. If the ledge BC has a gentle descent, it may reflect not the frontal wave, but the direct wave incident directly from the point of explosion O_2.

In concluding the examination of the interpretaion of longitudinal hodographs in the case of a step, we note that in practice it is far from always possible to realize all the foregoing constructions, since for the most part they are based on the use of diffraction-type waves, clear recordings of which are obtained frequently only with great difficult. Nevertheless, the principal information on the step -- the position of its upper edge in plane and the height of the ledge -- can usually be obtained.

Attention should be called to the independent determination of the boundary velocities B_b (V_2) of parts of the refracting layer on the two sides of the step. If these velocities are found to be substantially different, and particularly if the velocity V_b on the dropped portion of the step is found to be less than on the raised one, doubts can be raised of whether both parts of the step belong to one and the same stratigraphic or lithological level.

If it is too difficult to obtain a sufficiently reliable and detailed interpretation of longitudinal hodographs along the profile located across the lines of the step, then the prospecting of the step can be carried out, as indicated in Chapter III, Section 5, with the aid of a system of longitudinal and non-longitudinal profiles, for example, by means of two longitudinal profiles which do not intersect the step and which are located along it on the raised and lowered portion, and a transverse profile, which cuts through the line of extent of the step.

7. Presentation of the Graphical Material

The technique of representation of the graphical material, obtained as a result of observations in the CMRW, differs little from that used in the method of reflected waves (see instruction of reference [44]).

Nevertheless, the CMRW has certain specific features in this respect, connected principally with the greater range of depths, which are accessible to prospecting by use of refracted waves, and also with the fact that in the CMRW one investigates not only the placement of seismic boundaries, but also the values of the velocities in the layers.

Representation of the hodographs, scales. In prospecting at small depths (100--200 meters) it is recommended that the hodographs be constructed on the following scale: horizontal 1:5000 and vertical 1 cm = 0.01 sec or 1 cm 0.02 sec. In prospecting at medium depths (approximately 1 km) the scales usually used are horizontal 1:10,000 and vertical 1 cm = 0.05 sec. In prospecting of great depths (2 -- 3 km and greater) smaller scales are used: horizontal 1:20,000 and vertical 1 cm = 0.1 sec. We note that the scales 1:25,000 (for distances) and 1 cm = 0.04 sec (for time) are inconvenient and should be avoided.

The coordinate axis on the hodographs are marked by distances in meters or kilometers and by times in seconds. The place of each point of explosion is fixed by an arbitrary symbol and by drawing a vertical line (time axis). The hodographs are plotted by means of points which are then joined by smooth lines. On these are marked the points of the break in the correlation and other features of the record in accordance with the seismograms. Usually for each wave one constructs one phase hodograph, but when going from one phase to another on a certain section of the profile (which occupies not less than one or two stations of seismographs) one constructs hodographs of both phases. The hodographs are marked by symbols of the same color with which the phase (wave) is designated on the seismogram.

The phase hodographs are used to determine the apparent velocities for individual branches close to linear; these values of the velocities are written out above the hodograph lines.*

Mapping of the sections. The seismic sections obtained as a result of the interpretation of longitudinal hodographs are mapped as a rule in non-distorted scales, and usually these scales are the same as the distance on the hodographs. The final seismogeological sections, where the seismic data are compared with the geological ones, can be represented on smaller scales, for example 1:25,000 or 1:50,000 but naturally, not on larger scales than these with which the primary constructions have been made.

On seismic sections one maps the refracting boundaries,

* The sequence of introducing corrections in the observed hodographs is described in Chapter V, Section 2.

under which the values of the boundary velocities are written (see, for example, Fig. 76). The values of the average velocities (above the boundary) or the layer velocities (between the boundaries, in the middle of the layer) are also marked. The sections of the boundary with different boundary velocities are separated from each other by means of transverse rules.

The sections should represent graphically the degree of reliability of the obtained results. Sections of the boundaries constructed by means of opposing hodographs are more reliable and are shown with heavy lines, and those obtained from individual hodographs are shown with thin lines. The less reliable boundaries are shown dotted.

Chapter VI

INTERPRETATION OF NON-LONGITUDINAL HODOGRAPHS

1. The Three Dimensional Problem of Interpretation of Hodographs of Refracted Waves

In the investigation of refracting boundaries with large angles of inclination ($\varphi > 10^{\circ}$) use of the methods of interpretation which are designed for the solution of two dimensional (plane) problems can lead to great errors in the determination of the angles of inclination and depths of the investigated boundaries. In particular, if the section constructed along a longitudinal profile with the aid of the methods described in Chapter V pertains to a vertical plane passing through the profile line, this can lead to a considerable distortion in the shape and depth of the refracting boundary. The particularly large errors in the determination of the configuration of the refracting boundaries are possible in the case of non-plane separation boundaries with considerable angles of descent, if an investigation of this boundary is carried out only with the aid of longitudinal profiling. Therefore, as indicated in Chapter III, at considerable angles of inclination of refracting boundaries, longitudinal profiling must be supplemented by other systems of observation - transverse profiling or area measurement with one common point of explosion. In the interpretation of hodographs, obtained by these systems of observations, it is necessary to go over from an examination of two-dimensional (plane) problems to the consideration of three dimensional (spatial) problems.

Exact method of solving the three dimensional problem of interpretation of hodographs of refracted waves are given in reference [3] for the case of a plane separation boundary and in reference [6] for a separation boundary of arbitrary form.

form.

The method of solving the three-dimensional problem for the case of a plane boundary of separation is simple and can be readily employed in practice; we shall stop to consider it in Section 2. The method of solving the spatial problem for separation boundaries of arbitrary form is cumbersome and not suitable for large scale calculations in production work. We shall therefore not stop to examine this method and we shall consider for the separation boundaries of arbitrary shapes only the approximate methods of solution of the three dimensional problem [2, 17], which at the present time are used in large scale production work. These approximate methods have been developed in application to such systems of observations, as transverse profiles, and area measurement for one and the same explosion point.

<u>Principal premises in the interpretation of transverse hodographs and surface hodographs</u>. For a unique interpretation of transverse hodographs and surface hodographs (isochron maps) it is necessary to introduce more assumptions concerning the structure of the investigated medium, than in the interpretation of longitudinal hodographs. These assumptions can be divided into two groups: 1) assumptions concerning the velocities in the covering medium and along the refracting boundary; 2) assumptions concerning the structure of the refracting boundary in the zone between the point of explosion and the line of observation for the transverse hodograph or the region of observations for the surface hodograph.

<u>Assumptions concerning the velocities</u>. In the interpretation of transverse hodographs and isochron maps the following have to be given: a) the average velocity V in the covering medium and b) the boundary velocity V_b along the refracting boundary. In the case of a multiply-layered medium, consisting of layers of sufficiently large thickness with different velocity of elastic wave propagation, in the interpretation of transverse hodographs and isochron maps it is necessary to know the following: a) the layer velocities V_i in each of the layers and b) the boundary velocities V_i in each of the layers and c) the boundary velocities V_i along each of the separation boundaries. As a rule, the boundary velocity V_{bi} along the refracting boundary is always greater than the layer velocity V_i in the same layer.

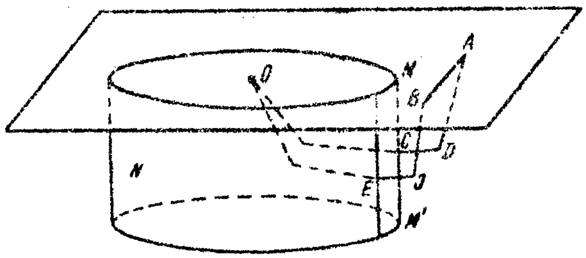

Fig. 87. Vertical cylinder N. The time of arrival τ of the wave propagating the refracting layer to the points E and C of the lateral surface of the cylinder is constant. CDA and EIB are the trajectories of the rays of the wave that arrives at the points A and B of the transverse profile.

Methods of interpretation of transverse hodographs and isochron maps discussed in Sections 3, 5, 6, and 7 are based on the assumption that all the layer and boundary velocities are constant and specified. In addition, for transverse hodographs we consider in Section 4 the case when the layer velocity in the medium covering the refracting boundary is a specified function of the depth H.

We note that in a case of a refracting boundary which is little inclined from the horizontal plane, it is possible to determine the boundary velocity V_b from the average velocity $\overline{V}$ in the covering medium and the boundary velocity V_b, if the initial points of the traced wave are obtained [5]. These cases, wherein it is possible to determine the velocities in the investigated medium from the transverse hodographs and from the isochrone maps, are encountered in practice relatively rarely; therefore in the interpretation of these hodographs the values of the velocities must be obtained from some other data or the values of velocities which are most probable for the given region must be assumed.

<u>Assumptions concerning the structure of the medium in the zone between the point of explosion and the line (or area) of observation.</u> The appropriate methods of interpretation discussed in Sections 3-7 are based on the assumption that the differences in arrival time of the waves at different points of the profile or at the surface of obser-

vations, located at equal distance to the point of explosion, is due only to the differences in the relief of the investigated refracted boundaries and all the separation boundaries above it in the zone of emergence of the seismic rays from the refracting boundaries. This assumption is based on the following schematization of the structure of the medium in the zone between the point of explosion and the line (or region) of observations:

1) The time of arrival τ of the wave, propagating in the refracting layer, to the lateral surface of the vertical circle and cylinder N with axes passing through the point of explosion, is constant (Fig. 87); this surface is located near the zone of emergence of the rays from the refracting layer.

2) In the zone of emergence of the rays from the refracting layer, the separation boundary (in the case of a two-layer medium) and all the separation boundaries can be represented in the form of horizontal steps, located at different depths. The rays that glide along these steps are denoted in Fig. 87 by the letters CD and EI.

Under these assumptions with respect to the construction of the medium in the zone between the point of explosion and the lines of observation and concerning the velocities in all the media, the transverse hodographs and the isochrone maps can be interpreted practically uniquely.

2. Determination of the Elements of Location of a Plane Inclined Refracting Boundary

In case of a plane inclined refracting boundary the rays of the incident gliding and refracted waves lie in the plane ABDC (Fig. 88), passing through the line of the profile AB normal to the separation boundary. This plane coincides with the vertical plane ABIE, which passes through the profile line, only in that case when the direction of the profile Ax' coincides with the direction of incidence Ay of the separation boundary; in all cases these planes do not coincide. Therefore, if the sections which are constructed on the basis of two opposing hodographs are represented for the plane normal to the separation boundary in the vertical plane passing through the line of the profile, the depth and the angles of inclination of the refracting boundaries will be distorted. At large angles of inclination of the

refracting boundary ($\varphi \geq 30^o$), the errors in the determination of the depth and of the angles of inclination reach considerable values.

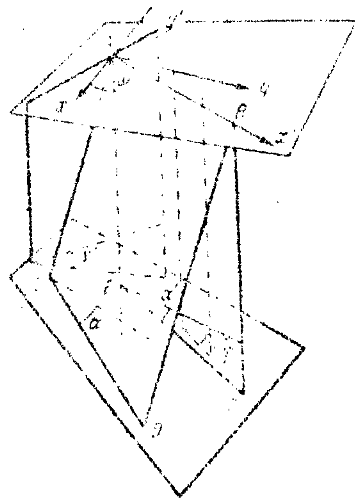

Fig. 88. Location in space of the vertical (ABIE) and normal (ABDC) planes, passing through the line AB of the longitudinal profile. Ax - direction of the refracting boundary; Ay - direction of drop; - total angle of incidence of the refracting boundary; α - angle of drop of the boundary in the normal plane ABDC; α' - angle of drop of the boundary in the vertical plane ABIE; γ' - angle of drop of the boundary in the vertical plane, passing through the line Ay' of the transverse profile.

<u>Systems of obsrevation necessary for unique interpretation</u>. To determine the elements of location of the plane inclined refracting boundary - the direction and angle of drop and depth of its location - the system of two opposing hodographs is insufficient, with the exception of the particular case when the direction of the profile coincides with the direction of drop of the separation boundary. As shown in reference [3], to determine the elements of location of a plane inclined refracting boundary and the boundary velocity V_b, one must have three elements of linear hodographs, obtained in different directions x_s, and these hodographs can be obtained both with a common explosion points (Fig. 89a) and with different explosion points (Fig. 89b). Each of the elements of the hodographs should be used to deter-

mine the parent velocity dx_s/dt. To determine the direction and angle of drop and depth of its location - the system of two opposing hodographs is insufficient, with the exception of the particular case when the direction of the profile coincides with the direction of drop of the separation boundary. As shown in reference [3], to determine the elements of location of a plane inclined refracting boundary and the boundary velocity V_b, one must have three elements of linear hodographs obtained in different directions x_s, and these hodographs can be obtained both with a common explosion point (Fig. 89a) and with different explosion points (Fig. 89b). Each of the elements of the hodograph should be used to determine the parent velocity dx_s/dt. To determine the direction and angle of drop, and also the boundary velocity V_b, it is enough to know only the value of the apparent velocities dx_s/dt ($s = 1, 2, 3$). In addition, to determine the depth H of the refracting boundary it is necessary to know the time t of arrival of the wave at one point of one of the profiles x_s. In the determination of the foregoing quantities the velocity V_1 in the covering medium is assumed to be constant and specified. It is possible to indicate many systems of observations, which are convenient from the practical point of view for the solution of this problem. The most convenient for the correlation interrelation of the waves is the following system: two elements of opposing longitudinal hodographs and one transverse hodograph element, wherein one of the longitudinal hodographs and the transverse hodographs are obtained for a common point of explosion (Fig. 89b), i. e., an element of the surface hodograph is obtained at this point of explosion. Let us consider for this system of observation the methods of determining the direction and the drop angle φ, the depth H of location of the refracting boundary, and the boundary velocity V_b.

In this examination, let us introduce a left-handed system of coordinates, the origin of which is located at the point of intersection of the longitudinal and transverse profiles. We direct the x axis along the separation boundary, the y axis along its drop. The line Ox of the longitudinal profile 1, the shooting of which is carried out at explosion point 1 (EP1), makes an angle ω with the direction of x (Fig. 90a, b).

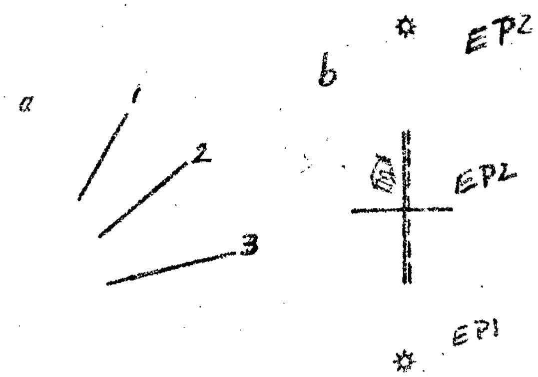

Fig. 89. System of observation necessary to determine the elements of location of a plane inclined refracting boundary. a - three longitudinal profiles, shooting of which is carried out with one common point of explosion; b - longitudinal and transverse profiles (solid lines), the shooting of which is carried out at an explosion point EP1 and a longitudinal profile (dotted line), the shooting of which is carried out at an explosion point EP2.

<u>Connection between the quantities dt/dx_s, the reciprocals of the apparent velocities, and the angle of inclination of the refracting boundary</u>. For two opposing longitudinal hodographs, the quantities dt/dx_s, which are the reciprocals of the apparent velocities of propagation of the wave front along the corresponding lines of observation, are expressed by the following formulas

$$\frac{dt_1}{dx'_1} = \frac{\sin(i_{12} + \alpha)}{V_1} \qquad (27)$$

$$\frac{dt_2}{dx_2} = \frac{\sin(i_{12} - \alpha)}{V_1}$$

where α is the angle of inclination of the refracting boundary in a plane passing through the line of the longitudinal profile normal to the separation boundary (Fig. 88); $i_{12} = \sin^{-1}(V_1/V_b)$ is the critical angle. The quantity dt_1/dy', which is determined from the transverse hodograph, is given by the formula

$$\frac{dt_1}{dy'} = \frac{\cos(i_{12}+\alpha)}{V_1} \sin \gamma' \qquad (28)$$

where γ' is the angle of drop of the refracting boundary in the vertical plane passing through the line Ay' of the transverse profile (Fig. 88). If the elements of the two hodographs (longitudinal and transverse) are obtained for one common explosion point, then, using formulas (27) and (28), it is possible to obtain the following expression for the angle γ'

$$\sin \gamma' = \frac{\frac{dt}{dy}}{\sqrt{\frac{1}{v_1^2} - \left(\frac{dt}{dx}\right)^2}} \qquad (29)$$

Thus, having determined the apparent velocities from three hodograph elements, it is possible to determine the angle of inclination α and the normal plane, passing through the line of longitudinal profile, and the angle of inclination γ' in the vertical plane, passing through the line of transverse profile.

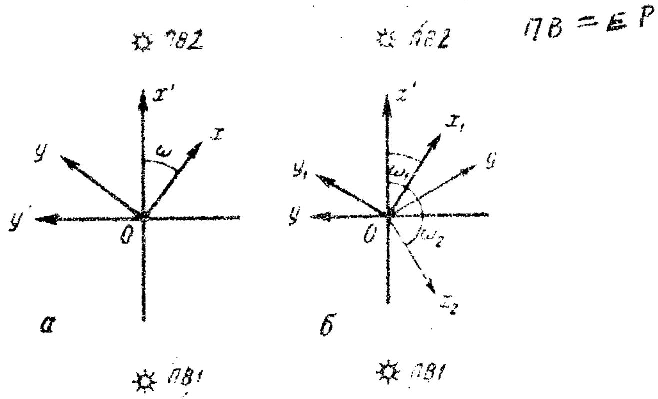

Fig. 90. a - location of the line of logitudinal profile Ox' and the transverse profile Oy' relative to the di-

rection of the extent Ox and drop Oy of the refracting boundary; b - determination of the physical real root. Ox_1 and Oy_1 - directions of extent and drop, corresponding to the root ω_1; Ox_2 and Oy_2 - directions of extent and drop corresponding to root ω_2.

Determination of the total angle of drop of the refracting boundary. Knowing the angles α and γ', one calculates the total angle of descent from the following formula

$$\sin\varphi = \sqrt{\sin^2\alpha + \sin^2\gamma'\cos^2\alpha} \qquad (30)$$

Determination of the direction of extent and drop of the refracting boundary. The angle ω between the direction of the extent of the refraction boundary and the direction of the profile, reckoned from the direction of the profile Ox' clockwise, is determined from the formula

$$\sin\omega = \frac{\sin\alpha}{\sin\varphi} \qquad (31)$$

As can be seen from this formula, for a specified value of the angle α there exists two values of $\omega(\omega_1$ and $\omega_2)$ which satisfy the Eq. (31). For $\alpha > 0$ these values are as follows: $0 < \omega_1 < \frac{\pi}{2}$ & $\omega_2 = \pi - \omega_1$. At $\alpha < 0$ there also exist two roots of the Eq. (31):

$$\frac{3\pi}{2} < \omega_1 < 2\pi \text{ and } \omega_2 = 2\pi - (\omega_1 - \pi)$$

The choice of the physically real root is based on a comparison of the signs of the angles α and γ', obtained for the different values of the Azimuth ω, with the signs of these angles as determined from the observed hodographs.

By way of an example we show in Fig. 90b two possible directions of the extent Ox_1 and Ox_2, forming respectively angles ω_1 and $\omega_2 = \pi - \omega_1$ with the line Ox', and the corresponding two directions of drop Oy_1 and Oy_2. The signs of the angles α and γ' are determined by the signs of the projections of the vector of descent Oy_1 or Oy_2 respective-

ly on the directions Ox and Oy'. From the diagram it is seen that when $0<\omega_1<\frac{\pi}{2}$ we have $\alpha>0$ and $\gamma'>0$; for $\omega_2=\pi-\omega_1$, we have $\alpha>0$ and $\gamma'<0$, i. e., for both values of ω_1, which are roots of the Eq. (31) the signs of the angle γ' are different. Comparing the signs of the angle γ', obtained for both values of the root ω, with the sign of the same angle obtained by formula (29), we can choose the physically real root ω.

Table 8 indicates the signs of the angles α and γ' for all values of ω from 0 to 2π.

Table 8

Азимут профиля[1]	α	γ'	Азимут профиля	α	γ'
$\omega=0$	0	+	$\omega=\pi$.	0	—
$0<\omega<\frac{\pi}{2}$.	+	+	$\pi<\omega<\frac{3\pi}{2}$.	—	—
$\omega=\frac{\pi}{2}$	+	0	$\omega=\frac{3\pi}{2}$	—	0
$\frac{\pi}{2}<\omega<\pi$.	+	—	$\frac{3\pi}{2}<\omega<2\pi$	—	+

1) Azimuth of the profile.

From an examination of this table it is seen that the ratio of the signs of the angles α and γ' is different for two values of ω which are roots of the Eq. (31). Thus, making use of the sign rule, it is possible to determine uniquely the physically real root of the Eq. (31), i. e., to determine uniquely the direction of extent of the separation boundary. Knowing the direction of the extent, it is possible to determine graphically the direction of the drop of the refracting boundary.

<u>Determination of the boundary velocity V_b</u>. The limiting angle i_{12} is determined by means of two opposing longitudinal hodographs simultaneously with the determination of the angle α. Calculating with the aid of formulas (27) the value of i_{12}, and knowing the velocity V_1, one determines the boundary velocity V_b.

Determination of the depth of the refracting boundary. The depth H of a plane refracting boundary along the normal under the point O of intersection of longitudinal and transverse profiles are determined from the formula

$$H = \frac{t - \frac{x}{V_1}\sin(i_{12} - \alpha)}{2\cos i_{12}} V_1. \qquad (32)$$

Knowing the depth H along the normal and the angle of inclination φ, it is possible to find the depth H_V along the vertical by means of the formula

$$H_B = \frac{H}{\cos\varphi} \qquad (33)$$

Since by definition the separation boundary is plane, than, knowing the depth at one point, we can find the depth at any other point by means of the formula

$$H_B(x) = H_B(0) + x \operatorname{tg}\alpha', \qquad (34)$$

where α' is the angle of inclination of the separation boundary in the vertical plane, passing through the line joining the two points AB under consideration (Fig. 88), and x is the distance between the two points.

The angle ω is connected with the angle of drop φ and the azimuth of the considered line, reckoned from the direction of extent of the separation boundary, by the following relation

$$\operatorname{tg}\alpha' = \operatorname{tg}\varphi \sin\omega; \qquad (35)$$

and consequently

$$H_B(x) = H_B(0) + x \operatorname{tg}\varphi \sin\omega \qquad (36)$$

Formula (36) makes it possible to determine at any point the depth of a plane refracting boundary, if the depth H and the angles φ and ω are calculated for one point of this boundary.

3. Interpretation of Transverse Hodographs in the Case of a Single Boundary at Constant Velocities V_1 and V_2

<u>On the determination of the difference in depth at different points of the transverse profile.</u> Under the assumptions regarding the structure of the medium as indicated in Section 1, the difference in depth ΔH of the refracting boundary at the zone of emergence of the rays from the second medium, determined from the two points A and B of the transverse profile (Fig. 91 and 92) equally remote from the point of explosion, is expressed by the following formula [1. 3, 4]:

$$\Delta H = \Delta t \frac{V_1}{\cos i_{12}}, \tag{37}$$

where Δt is the difference in time of arrival at the two points under consideration; $i_{12} = \sin^{-1} (V_1/V_b)$; V_1 and V_b are respectively the velocity in the covering medium and the boundary velocity in the refracting layer.

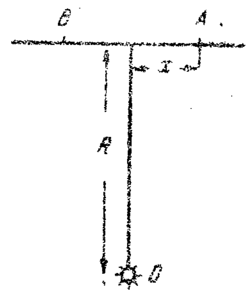

Fig. 91. Scheme of location of the point of explosion O relative to the line of transverse profile. The point A and B are at equal distances from the point of explosion.

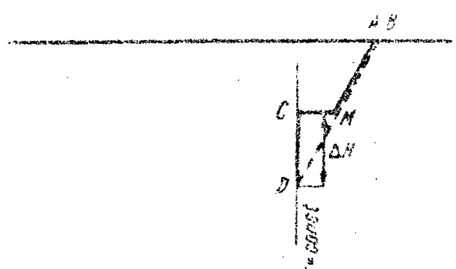

Fig. 92. Determination of the difference H of the depths of the refracting boundary at the points M and D of

-L-

the emergence of the seismic rays from the refracting layer, corresponding to the points A and B of the transverse profile. The line τ = const is the line of equal times of arrival of the wave, extending in the refracting layer. The solid line - the trajectory CMA of the rays of the wave, arriving at the point A. The dotted line is the trajectory DB of the rays of the wave arriving at the point B.

If the observations are carried out along a straight-line transverse profile, the points of which are located at different distances from the point of the explosion, then under the assumptions indicated above with respect to the constancies of the velocities V_1 and V_b and with respect to the structure of the medium in the zone between the point of explosion and the lines of the profile, the difference in the times of arrival of the wave at the different points of the profile is caused by two factors:

1) the change in the relief of the refracting boundary in the zone of emrgence of seismic rays from the second medium;

2) differences in the distances from the point of explosion to the different points of the profile.

In order to determine the relief of the refracting boundary in the zone of emergence of the rays from the second medium, it is necessary to eliminate from the observed difference in times Δt of the arrival at the different points of the profile the difference of times Δt_0, due to the differences in the distances from these points to the point of explosion. To eliminate the variation in the distance from the point of explosion to the different points of the transverse profile, we introduce the concept of the normal hodograph.

<u>The normal hodograph</u>. A normal trabsverse hodograph is called the curve of difference and time of arrival of the refracted wave at different points of a straight-line transverse profile, calculated for the case of a horizontally refracting boundary. The equation of the normal hodograph has the following form

$$\Delta t_0 = \frac{R}{V_б}\left[\sqrt{1 + \left(\frac{x}{R}\right)^2} - 1\right], \qquad (38)$$

where R is the distance from the point of explosion to the profile, measured along the perpendicular to the line of the profile (Fig. 91); x is the distance from the base of the perpendicular to any point of the profile.

The normal hodograph (38) characterizes the variation in the time of arrival along the line of the transverse profile only due to the change in the distance from the point of explosion to the different points of the profile.

For convenience in interpretation, it is necessary to construct templates of normal hodographs (Fig. 93). In those cases when on different transverse profiles one assumes one and the same value of the distance R to the point of explosion, and when the waves registered are characterized by different values of the boundary velocity V_b, one constructs a template of hodographs for a specified value of R and for different values of the parameter V_b. In those cases when the used distances R are different and one wave with a constant velocity V_b is traced, a template is constructed for a specified value of V_b and for different values of the parameter R. Finally, several templates of normal hodographs are constructed in those cases when several waves, corresponding to separation boundaries with different values of V_b are traced, or when the values of Vb for one and the same boundary are different at different sections and the employed distances R are also different.

Elimination of the normal hodograph. To eliminate the influence of the variation of the distance from the point of explosion to different points of the transverse profile on the shape of the observed hodograph, it is necessary to substract from the observed hodograph the normal hodograph. The normal and observed hodographs are plotted in the same scale as indicated in Chapter V for the construction of longitudinal hodographs. The elimination of the influence of the distance is carried out in the following manner. On the template of the normal hodographs one chooses a hodograph constructed for that value of R, at which the observed hodograph was obtained, and for that value of the boundary velocity V_b. This normal hodograph is substracted graphically from the observed one. The substraction is performed in the following manner: any one point of the observed hodograph is made to coincide with the point of the normal hodograph, located at the same

distance from the points of explosion (Fig. 94). One determines graphically the difference in time Δt_1 for all the points of the observed and normal hodographs, located at equal distances $\Delta = \sqrt{R^2 + x^2}$ from the point of explosion. The obtained values t_1 under the assumptions made above can be ascribed in their entirety to the relief of the refracting boundary at the zone of emergence of the seismic rays from the second medium.

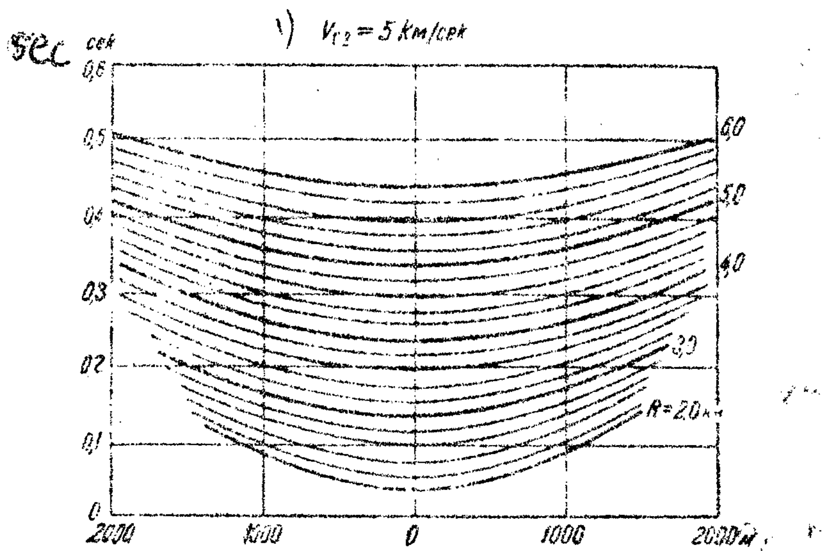

Fig. 93. Template of normal hodographs, constructed for a constant value of the velocity V_b; the parameter of the family of curves is the distance R from the point of explosion to the line of the profile.
1) V_{b2} = 5km/sec.

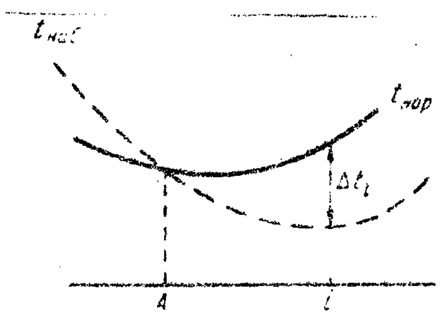

Fig. 94. Elimination of the normal hodograph t_{nor} from the observed hodograph t_{obs}.

Determination of the relief of the refracting boundary in the zone of emergence. After substracting the normal hodograph it is possible to determine for each point of the profile the change in depth ΔH_i of the points of the refracting boundary in the zone of emergence, relative to the point M of the separation boundary (fig. 95), to which corresponds the point A of the observed hodograph, made to coincide with the point of the normal hodograph. For this purpose the quantities Δt_1, obtained after substracting the normal hodograph, must be multiplied, in accordance with formula (37), by a factor V_1 (cos i_{12}). As a result of such calculations one obtains the relative relief of the refracting boundary in the zone of emergence.

To determine the absolute depth it is enough to know the depth for one reference point of emergence. It must be emphasized that the term "depth" is peculiar in the case of transverse profiles. The depth for a certain point of emergence, or simply depth at a certain point, will be called from now on the depth, measured from the point A of the transverse profile to the horizontal line passing through the point M of emergence of the seismic rays from the second medium (Fig. 95). The depth H_0 at the reference point can be determined from the data of the longitudinal profile or from boring data.

The depth H_k at any point of the profile is calculated from the formula

$$H_k = H_0 + \Delta H_k \qquad (39)$$

where ΔH_k is the difference in depth in the arbitrary and in the reference points of the profile.

Representation of the results of the determination of depths by means of the transverse hodograph. By means of the transverse hodographs, as already indicated, one determines the relief of the refracting boundary in the zone of emergence of the seismic rays from the second medium. Consequently, the points of the refracting boundary, for which the depths are calculated, do not lie strictly speaking in a single plane. However, to obtain a clear representation of the shape of the refracting boundary in the interpretation of transverse hodographs, one plots a section in one vertical plane - the plane passing through the line of the transverse profile. This construction is later on used to

plot the depths on the map. As will be shown below, such an arbitrary method of representing the sections makes it possible in many cases to determine the angles of the inclination of the refracting boundaries with sufficient accuracy.

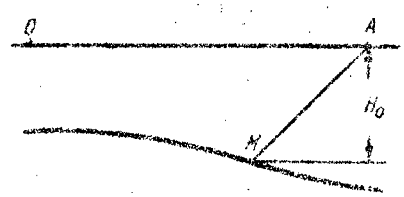

Fig. 95. Determination of the depths H_0 in the reference point.

The representation of the results of the determination of the depths by means of the transverse hodograph breaks up into two stages:

1) construction of the section in the vertical plane, passing through the line of the profile;

2) plotting of the depths or markers of the refracting boundary on the map. Let us stop to examine each of these operations.

Methods of constructing the section by means of the transverse profile. To construct the section of the refracting boundary it is necessary to construct first a leveling section of the surface of observation along the profile line. The calculated depths must be laid off directly from the leveling section.

The construction of the section can be carried out by two methods: 1) with allowance for the lateral deviation of the seismic rays from the vertical plane passing through the point of observation perpendicular to the lines of the transverse profile; 2) without allowance for the lateral deviation.

First method. From each point on the profile line as a center, a circle is drawn of radius equal to the depth

H_k, calculated for the given point (Fig. 96a). The envelope of this family of circles represents the sought refracting boundary.

Second method. The calculated depths are laid off along the vertical under each point of the profile, and a curve is drawn joining the ends of the laid off segments (96b).

A comparison of the accuracy of the determination of the angle of drop in the vertical plane passing through the line of the profile by both methods has been carried out in reference [1] for a plane inclined refracting boundary. This comparison has shown that the former method insures greater accuracy in two cases: 1) when the direction of the profile is close to the direction of the drop of the refracting boundary; 2) when the direction of the profile differs from the direction of the drop, wherein the separation boundary drops from the point of explosion in a direction towards the line of the profile.

The second method of construction insures a greater accuracy of the determination of the angle of incidence in those cases, when the direction of the profile differs from the direction of the drop of the separation boundary, and the refracting boundary rises in a direction from the point of explosion towards the line of the profile. In practice the former method is mostly used.

In the construction of sections by means of transverse hodographs, the same scales are used as in the construction of sections by longitudinal hodographs (Chapter V).

Plotting of the points of the refracting boundary, determined by the transverse profile, on the depth map or on the contour-lines. When locating the depths (or equal-contour lines) of the points of the refracting boundary on a map, plotted from a section constructed in the vertical plane passing through the line of the profile, it is necessary to take into account the corrections for the deviation of the point of emergence of the seismic ray from the second medium from the indicated plane. This correction is customarily called drift in seismic prospecting. In the interpretation of the transverse hodographs there are not wnough data for an exact calculation of the magnitude of the drift. It becomes therefore necessary to use approxi-

mate methods of calculating the drift.

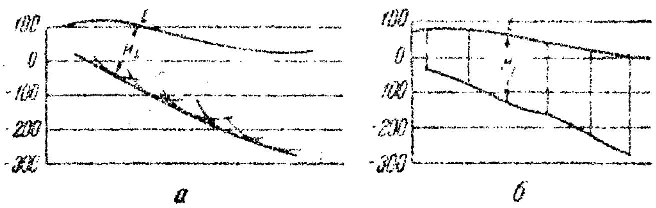

Fig. 96. Construction of sections by transverse hodographs with allowance of the lateral deviation of the seismic rays (a) and without allowance of the lateral deviation (b).

To calculate the drift it is necessary to perform two operations: 1) determine the magnitude L of the drift at each point of observation, 2) choose the direction in which the calculated magnitude must be laid off from the corresponding points of observation.

Determination of the drift values L_i. The value of the drift can be approximately calculated from the formula for the horizontal separation boundary

$$L_i = H_i \operatorname{tg} i_{12}, \quad (40)$$

where H_i is the depth along the vertical under the i-th point of the profile (Fig. 95).

Choice of the direction in which it is necessary to lay off the magnitude of the drift. In the general case the projection on the surface of observation of the point of emergence of the seismic ray from the second medium does not lie on the straight line during the point of explosion with the point of observation. Consequently, the magnitude of the drift, strictly speaking, should be measured in a direction different from the line joining the point of observation with the point of explosion. However, in the interpretation of transverse hodographs there are not enough data for the determination of the true position of the point of emergence of the ray and consequently to determine the true direction,

in which it is necessary to measure the magnitude of the drift. It becomes therefore necessary to use an approximate method, laying off the magnitude of the drift from the point of observation in a direction joining this point with the point of explosion. Technically this is carried out in the following manner.

On a plan containing the transverse profile and the point of explosion (Fig. 97) from which the shooting of this profile was made, one lays off the value of the drift L from each point A, B, etc. of observation along a line joining this point with the point of explosion. If the surface of observation represents a horizontal plane, then near each point A', plotted in the indicated manner on the plan, it is necessary to write down the value of the depth H, corresponding to this point. If the surface of observation differs from the horizontal plane, then the depth of refracting boundary H_i, calculated for the points of observation i, will differ in general from the depth H_K of the boundary, determined along the vertical at the point of emergence e of the seismic radiation from the second medium, corresponding to the point i of observation (Fig. 98). Therefore, in the presence of a surface relief it is necessary to write near the points plotted on the plan not the depth, but their markers taken from the transverse profile (Fig. 96) - the absolute markers or the markers relative to a certain arbitrarily assumed horizontal plane. These data will be later on used for the compilation of the structural map of the refracting boundary.

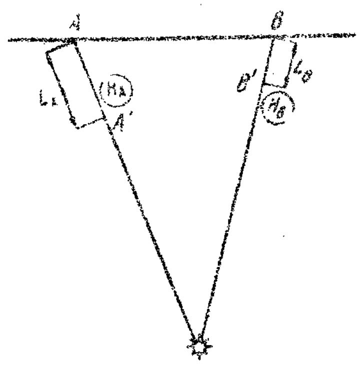

Fig. 97. Plotting the depths of the refracting boundary on a plan with allowance for the drift. H_A and H_B - depths calculated for the points A and B of the transverse

profile and marked on the plan near the points A' and B', plotted with allowance for the values of the drifts L_A and L_B.

Accuracy of determination of the angles of inclination for the transverse profiles. An analysis of the accuracy of the determination of the angles of inclination with the aid of the described method has been carried out for a plane inclined refracting boundary in references [2, 3]. In reference [3] the examination os carried out as applied to the case when the length of the profile is small compared with the distance R from the point of explosion to the line of the profile, and in reference [2] the analysis of the accuracy is carried out for profiles of arbitrary length.

When the profile is short compared with the distance R, the angle of inclination γ'_Φ, determined along the section plotted in the vertical plane ABIC passing through the line of the profile (Fig. 99), differs at inclination angles on the order of 10-20° from the true angle of inclination γ' in the same plane by not more than 2 or 3°, and only at large angles of inclination ($\varphi >$ 20°) does the value of $\Delta\gamma = \gamma'_\Phi - \gamma'$ reach a magnitude of 7° and more.

In calculating the drift, the section constructed in the vertical plane ABIC, passing through the line of the profile, is transferred to the other plane A'B'NK, which we shall call the drift plane (Fig. 99). Calculations have shown that at angles of inclination $\varphi \leq$ 15° the calculation of the value of the drift by formula (14) yields a sufficiently accurate angle of inclination χ in the drift plane. The deviation of the determined value, χ_Φ, from the true value of the angle χ in the drift plane does not exceed 1°. At inclination angles $\varphi >$ 15°, in order to prevent distortion of the inclination angles, the value of L as determined by formula (40) must be multiplied by a certain coefficient n, the so-called coefficient of optimum drift. The magnitude of the coefficient n depends on the angle of inclination φ and on the location of the profile relative to the direction of the drop of the refracting boundary. When the refracting boundary drops from the point of explosion towards the line of the profile, and $n > 1$, and in the case of a rise $n < 1$ [3].

In the case of profiles of arbitrary length, this method of interpretation insures sufficient accuracy of

the determination of the angles of inclination in those cases, when the angle of inclination is $\varphi < 15^{\circ}$. At larger angles of inclination, when using this method, the angle of inclination is not only in error, but the straight-line refracting boundary becomes curved. This curvature is particularly significant in the case of a transverse profile of great length and represents a serious danger in the interpretation, since it may lead to incorrect conclusions concerning the shape of the structures - on the leveling out or, to the contrary, on the increasing of the slopes of the wings of the foldings, on the presence of gently sloping anticlinal foldings, etc. To reduce these distortions, it is proposed in reference [2] that in the interpretation of the transverse hodographs one eliminate the normal hodograph, which differs from the hodograph determined by Eq. (38). This hodograph is called the average normal hodograph for inclined separation boundary. The elimination of this average normal hodograph from the observed hodograph increases the accuracy of determination of the angle of inclination, reduces considerably the curving of the refracting boundary, and makes it possible to use longer profiles for the interpretation, than in the elimination of the normal hodograph for the horizontal separation boundary. We shall not stop here for a more detailed examination of this method, since the cases of large angles of inclination ($\varphi > 15^{\circ}$) are encountered in seismic prospecting practice relatively rarely.

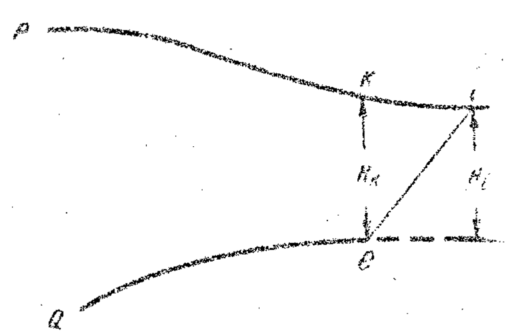

Fig. 98. Determination of the depths of the refracting boundary in the zone of emergence in the presence of a surface relief.

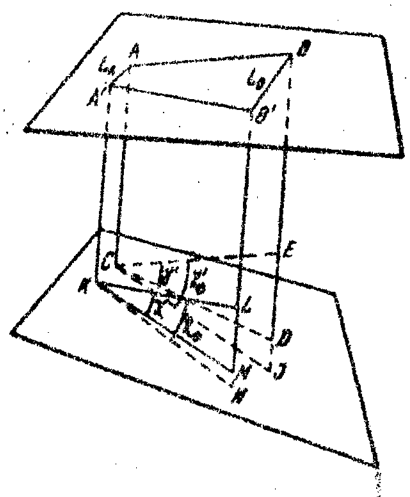

Fig. 99. Determination of the position of the plane ABNK of the drift. ABIC - the vertical plane, passing through the line AB of the transverse profile; γ - true angle of incidence of the refracting boundary in the vertical plane ABIC; γ_Φ - angle of drop of the refracting boundary, obtained in the interpretation of the transverse hodograph; χ - true angle of incidence of the refracting boundary in the drift plane; χ_Φ - angle of incidence in the drift plane, obtained in an interpretation of the transverse hodograph with allowance for the drift.

<u>Determination of boundary velocities from transverse hodographs</u>. In the case of a separation boundary that deviates little from a horizontal plane, at a specified distance R, the shape of the transverse hodograph depends only on the magnitude of the boundary velocity V_b, and therefore it is possible to determine from the photograph uniquely the values V_b. This determination is most conveniently carried out by graphic means. On a template of a normal hodograph, constructed for a specified value of R at different values of the parameters V_b, one superposes a traced observed hodograph and the normal hodograph that approximates the observed one in the best manner is selected (Fig. 100). The parameter V_b of this approximating hodograph is the sought value of the velocity V_b.

In the case of an inclined separation boundary the

determination of the boundary velocity by transverse hodographs, as shown by calculation, leads to great errors at relatively small angles of inclination, on the order of 5°. Therefore the determination of V_b by means of transverse hodographs is best carried out only at small angles of inclination, $\varphi < 5^{\circ}$. In the case of curved separation boundaries the determination of V_b by transverse hodographs is usually impossible in practice.

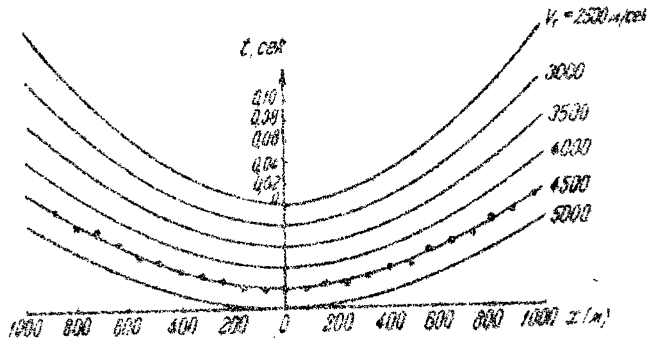

Fig. 100. Determination of the boundary velocity V_b by means of transverse hodographs. Curves - normal hodographs, constructed for R = const and V_b = var; circles - points of the observed hodograph.

4. Interpretation of Transverse Hodographs in the Case of Variation of the Average Velocity with Depth

In the prospecting of media, characterized by a continuous (or intermittently continuous) variation of layer velocities, and in this connection also of the average velocities $\bar{V}$ with depth H, it is possible to interpret the transverse and generally the non-longitudinal hodographs of refracted waves with allowance for this variation.

The law of dependence of the average velocity on the depth, $\bar{V} = \bar{V}(H)$ is assumed specified. It may be known, for example, on the basis of summary data of seismic carottage, the method of reflected waves, and the CMRW (see Chapter V, Section 3).

We shall assume, as was done in the case of a constant velocity (p 170 [of source]) that the differences in the times of arrival of the refracted waves at points of the non-longitudinal profile which are equidistant from the point of explosion is due only to the difference in the depth of the separation boundary in the region of reception, and that the boundary is plane and horizontal in the region of emergence of the ray.

The problem will consist of determining the depth H and the drift L for specified points of the non-longitudinal profile, where the times T of the arrival of refracted waves are observed, if in one of the points of this profile (or in any other point, see below) the depth H is known and is equal to H_0.

Let t be the marker of any one isochrone on the horizontal boundary for the wave propagation along this boundary with a boundary velocity V_b, T - the time of arrival of the refracted wave at the arbitrary point x_1 of the non-longitudinal profile; L - the magnitude of the drift. Then, according to Fig. 101, we shall have

$$T = t + \frac{l - L}{V_r} + \frac{H}{\bar{V} \cos i}, \tag{41}$$

where V is the average velocity ahead of the separation boundary, located at a depth H

$$\sin i = \frac{\bar{V}}{V_r}, \tag{42}$$

and l is the length of the segment, shown in the diagram.

From formulas (41) and (42) we obtain

$$H = \left(T - t - \frac{l}{V_r}\right)\frac{\bar{V}}{\cos i}. \tag{43}$$

We introduce the notation

$$\Delta T = T - t - \frac{l}{V_r}. \tag{44}$$

$$k = \frac{\bar{V}}{\cos i} \qquad (45)$$

Then we obtain from (43), (44), and (45)

$$\Delta T = \frac{H}{k} \qquad (46)$$

Here the values of $\bar{V}$, i, k, and Δ T are functions of H.

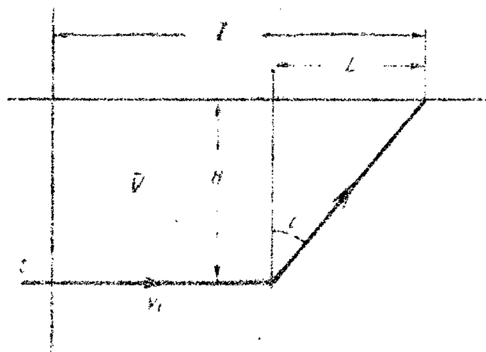

Fig. 101. Determination of the depths H_i.

For a specified law $\bar{V} = \bar{V}$ (H) and for a specified value of V_b it is possible to plot, with the aid of the foregoing formulas, the relationships between Δ T and H, and also between Δ T and L (the curves H and L on Fig. 103), with which one carries out the interpretation of the data along the non-longitudinal profile.

The curve H = H (Δ T) is plotted in the following manner. By specifying a definite value of H, we find on the graph $\bar{V} = \bar{V}$ (H) the corresponding value of $\bar{V}$; next, using formula (42), we find i, from formula (45) we find k, and finally, from formula (46), we find the corresponding value of Δ T. The values of H and Δ T determine the coordinates of one of the points of our graph. We then specify another value of H etc. As a result we plot the curve $H(\Delta T)$ point by point.

The graph $L = L(\quad T)$ is plotted analogously, using the following formula (see Fig. 101)

$$L = H \operatorname{tg} i,$$

where the value of i is chosen to correspond with H, as in the construction of the preceding curve.

Assume that the point x_0, where the depth $H = H_0$ is known, corresponds to the quantities l, T and ΔT, and that the point x_1, where we wish to determine the depth $H = H_1$ and the drift $L = L_1$ corresponds to the quantities L_1, T_1, and ΔT_1. We write out for these two points equations analogous to (44)

$$\Delta T_0 = T_0 - t - \frac{l_0}{V_r},$$

$$\Delta T_i = T_i - t - \frac{l_i}{V_r}. \qquad (47)$$

We note that the quantities ΔT_0 and ΔT_1 are fully determined by the deoths at the corresponding points.

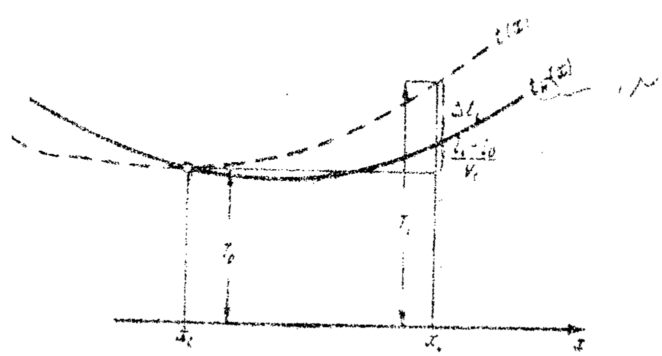

Fig. 102. Determination of ΔT; $t(x)$ - observed hodograph; t_n - normal hodograph.

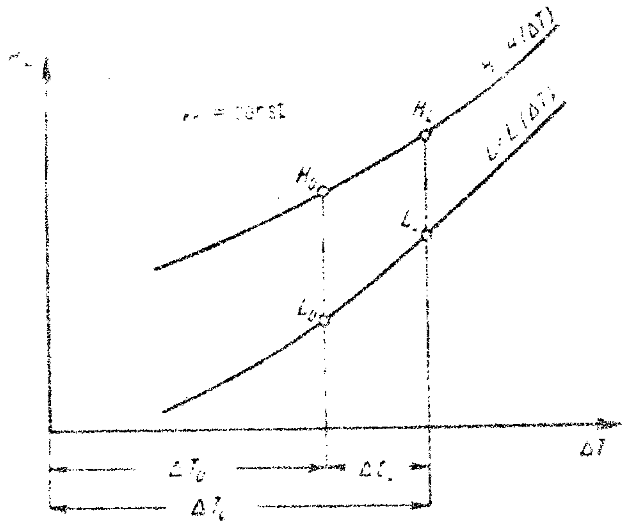

Fig. 103. Curves H (Δ T) and L = L (Δ T) for the determination of the depths H_i and the drifts L_i.

Let us substract these two equations term by term. As a result we obtain

$$\Delta t_i \equiv \Delta T_i - \Delta T_0 = (T_i - T_0) - \frac{l_i - l_0}{V_\phi}. \qquad (48)$$

The last term in this equation represents the difference in time on the normal hodograph between the point x_i of the non-longitudinal profile, at which it is required to determine H_i and L_i, and the point x_0, where the quantity $H = H_0$ is known (Fig. 102).

The determination of the values of H_i and L_i by the graph of Fig. 103 is carried out in the following manner. Placing together the point of the normal hodograph with that point x_0, T_0 of the observed hodograph, where the depth H_0 is known, we find, as shown in Fig. 102, the difference in times Δt_i between the observed and normal hodograph at the considered point x_i of the profile.

Turning now to the graphs on Fig. 100 we find on the curve H (Δ T) the point corresponding to the depth

H_0, and we note on the axis $\triangle T$ its abscissa $\triangle T_0$. We lay the segment $\triangle t_i$ from the point $\triangle T_0$, and find the abscissa $\triangle T_i$ of this point of the curve $H(\triangle T)$, the ordinate of which, H_i, is the sought one.

Thus, the depth H_i has been determined. The drift L_i is determined as the ordinate of the curve $L(\triangle T)$, corresponding to the same abscissa $\triangle T_i$.

The construction of the section over the transverse profile for known values of H_i, and the plotting of the points of the plan in the construction of the map of the equal depths with allowance for the drift L_i are carried out in the same way as described in Section 3 of this present chapter.

It must be noted that this method can be used for the interpretation of not only the transverse, but also any non-longitudinal or radial hodographs. In the latter case the normal hodograph will represent a straight-line hodograph for a plane horizontal separation boundary. The same method of determination of the depths H_i and the drifts L_i in the case of a variable velocity can be used also for the interpretation of isochrone maps, with the substraction of the normal hodograph from the observed one for the determination of $\triangle t_i$ at any point (x_i, y_i) on the plane being carried out in exactly the same way as in the case of the constant velocity (see Section 6 of the same chapter).

5. Interpretation of Transverse Hodographs in the Case of Multiply-Layered Media with Constant Velocities

In the analysis of the problem of interpretation of transverse hodographs, obtained in the study of multiply-layered media, we shall confine ourselves to the following two cases, which are most frequently encountered in practice: 1) the average velocity ahead of each of the refracting boundaries is constant along the line of transverse profiles; 2) the average velocity ahead of the refracting boundary changes along the line of the profile in connection with a change in the thickness of the different layers, covering the investigated boundary.

The first case is quite frequently encountered in

the investigation of media which are nearly horizontally stratified; quite frequently this case is encountered also in the presence of angular discrepancies between the refracting boundaries, if the refracting layers with the increased velocities are characterized by a small thickness and their presence hardly influences the magnitude of the average velocity ahead of the lower-lying refracting boundaries. In the case under consideration the interpretation of other transverse hodographs, corresponding to the different separation boundaries in a multiply-layered medium, is carried out with the aid of the method described in Section 3. Here the average velocity ahead of the different refracting boundaries may be either the same or different, depending on the velocity characteristics of the medium.

The second method is usually encountered in the investigation of media which differ from horizontally-stratified and which consist of relatively thick layers with different velocities. In this case, in the interpretation of the transverse hodograph corresponding to a certain separation boundary, it is necessary to take into account the refraction on the boundaries of the layers located above. We examine below the methods of interpretation of the transverse hodograph for this case under those assumptions regarding the structure of the medium, which were discussed in Section 1.

In the case of multiply-stratified media it is assumed in the interpretation of transverse hodographs, as in the interpretation of longitudinal hodographs (chapter V), that hodographs have been obtained for all the separation boundaries, located above the investigated boundary, and consequently that all the higher boundaries can be determined.

Let us examine first the case of two refracting boundaries, and let us proceed then to an examination of an arbitrary number of boundaries.

Two separation boundaries. There are given hodographs t_1 and t_2, corresponding to the first and second separation boundaries. The layer velocities V_1 and V_2 in the first and in the second layers are given, as are the boundary velocities V_{b2} and V_{b3} along the first and second separation boundaries. The layer velocity V_2 differs in general from the boundary velocity V_{b2}.

Under the assumptions indicated above regarding the constancy of the time of arrival τ of the wave to the generatrix MM' (Fig. 104) of the vertical cylinder, the difference Δt of the times of arrival of the wave, refracted by the second separation boundary, at two equidistant points of the tarnsverse profile, can be written in the following form

$$\Delta t_2 = \frac{\Delta H_1}{V_1} \cos i_{13} + \frac{\Delta H_2}{V_2} \cos i_{23}; \qquad (49)$$

where $H_1 = H_{1k} - H_{1i}$ and $\Delta H_2 = H_{2k} - H_{2i}$ is the difference in the thicknesses of the corresponding second and first layers in the zone of emergence of the seismic rays (Fig. 104).

$$i_{13} = \arcsin \frac{V_1}{V_{r3}}\ ;\ i_{23} = \arcsin \frac{V_2}{V_{r3}}. \qquad (49a)$$

If the observations are carried out along a straight-line transverse profile, then in order to exclude the influence of the change in the distance from the point of explosion to the different points of the profile on the course of the hodograph, it is necessary to substract from the hodograph the normal hodograph corresponding to the horizontal separation boundary constructed for the boundary velocity V_{b3}. In this case expression (49) represents the deviation of the observed hodograph, corresponding to the second separation boundary, from the normal hodograph. Assuming that the hodograph t_1, corresponding to the first refracting boundary, is given, we can, by using formulas (49) and (37), represent the change ΔH_2 in the thickness of the second layer in the following form

$$\Delta H_2 = \left(\Delta t_2 - \frac{\cos i_{13}}{\cos i_{12}} \Delta t_1\right) \frac{V_2}{\cos i_{23}}. \qquad (50)$$

where Δt_1 is determined from formula (37), i_{12} $\sin^{-1}$ (V_1/V_{b2}). If the quantity $k = \frac{\cos i_{13}}{\cos i_{12}}$ is close to unity, which takes place in particular at nearly equal values of the velocities V_{b2} and V_{b3}, or if $V_1/V_{b2} \ll 1$ and $V_1/V_{b3} \ll 1$, then formula (50) can be represented with sufficient accuracy in the form

$$\Delta H_2 = (\Delta t_2 - \Delta t_1)\frac{V_2}{\cos i_{23}} \qquad (51)$$

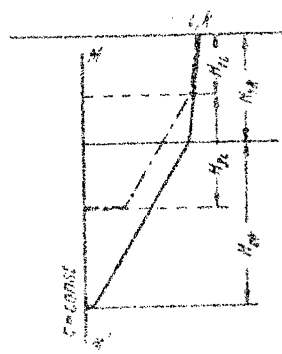

Fig. 104. Determination of the difference in the thickness of the second layer ΔH_2 for the points i and k of the transverse profile, located at equal distance from the point of explosion. The line τ = const is the line of equal times of arrival of the wave, propagating along the boundary of the third layer. The solid line is the trajectory of the rays of the wave, approaching the point k; the dash-dot line is the trajectory of the rays of the wave approaching the point i.

In this case, for points of profile i and k which are equidistant from the point of explosion, the difference $\Delta H_2^{i,k}$ in the thickness of the second layer is proportional to the increment in the difference between the times $\Delta t_2 - \Delta t_1 = (t_{2k} - t_{1k}) - (t_{2i} - t_{1i})$, determined by the hodograph corresponding to the first and second separation boundary (Fig. 105).

By means of formula (50), or by means of formula (51) in the case $k \approx 1$, we calculate the difference in thickness ΔH_2 of the second layer for different points of emergence of the seismic rays from the refracting layer. Knowing the thickness H_{02} for one of the points of emergence, it is possible to determine the value of the thickness in the zone of emergence for the entire profile by means of formula (39).

The construction of the section of the second refracting boundary in the vertical plane, passing through the line of the profile, is carried out with the aid of the second of the methods described above in the construction of a single

refracting boundary (Fig. 106), and in this construction, the quantities H_2 are laid off from the corresponding points of the first refracting boundary (Fig. 106).

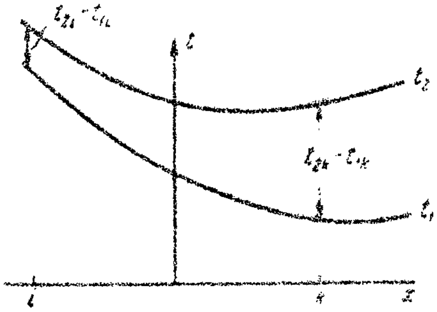

Fig. 105. Determination of the difference in thickness ΔH_2 for the points i and k at $\frac{\cos i_{13}}{\cos i_{12}} \approx 1$

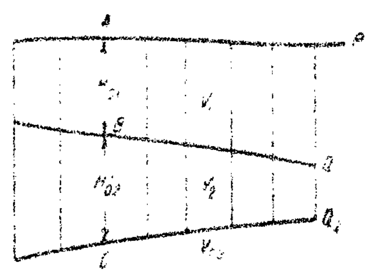

Fig. 106. Construction of the section by means of the transverse hodograph in the case of two refracting boundaries

To plot the obtained depths on the map, one calculates the value of the drift in accordance with the formula

$$L_2 = H_1 \operatorname{tg} i_{13} + H_2 \operatorname{tg} i_{23}. \qquad (52)$$

In the case of a horizontal surface of observation, the points for which the depths $H = H_1 + H_2$ are plotted on the map by the same method as in the case of a single refracting boundary. In the presence of a surface relief, which frequently takes place in the seismic prospecting process, it is necessary to mark the map not with deoth, but with absolute or relative markers of the points of the refrac-

ting boundary.

<u>Multiply-layered medium</u>. In the case of a multiply-layered medium with a separation boundary one can write the following system of equations:

$$\left.\begin{aligned} \Delta t_1 &= \frac{\Delta H_1}{V_1}\cos i_{12};\\ \Delta t_2 &= \frac{\Delta H_1}{V_1}\cos i_{13} + \frac{\Delta H_2}{V_2}\cos i_{23};\\ &\dots\dots\dots\\ \Delta t_n &= \sum_{k=1}^{n}\frac{\Delta H_k}{V_k}\cos i_{k,\,n+1} \end{aligned}\right\} \qquad (53)$$

where Δt_k ($k = 1, 2, \ldots$) is the deviation of the observed hodograph, corresponding to the k-th separation boundary, from the normal hodograph with the same boundary velocity; ΔH_k is the increase in the thickness of the k-th layer in the zone of emergence relative to a certain arbitrarily chosen point of emergence: $i_{1k} = \sin^{-1}(V_1/V_{bk})$; V_{bk} is the boundary velocity along the upper boundary of the k-th layer, V_k is the layer velocity in the k-th layer.

After determining successively the values of ΔH_k for each of the layers and after knowing for each of the layers the reference value of the thickness H_k at one point, it is possible, by using the methods indicated above, to construct the sections for all the refracting boundaries along the entire transverse profile. It is necessary to remember here that the boundaries shown on the section in one vertical plane actually do not lie in one plane, and the construction of the section is essentially only an auxiliary operation, necessary for the plotting on the map of the points with the calculated value of depths or the markers of the refracting boundaries.

The magnitude of the drift in the case of a multiply-layered medium is determined from the approximate formula

$$L_n = \sum_{k=1}^{n} H_k \operatorname{tg} i_{k,\,n+1}. \qquad (54)$$

The calculation of the drift is performed as indica-

ted in Section 3 in the examination of a single separation boundary.

6. Interpretation of the Isochrone Map in the Case of One Refracting Boundary at Constant Velocities V_1 and V_b

In the case of area surveys with one common explosion point, it is possible not only to interpret separately the data obtained on each of the profiles, representing the elements of the area survey, but also to interpret simultaneously the data obtained over the entire system of profiles. Unlike the profile measurement, at which one interprets hodographs along the observation line, i. e., linear hodographs, in the case of area surveys one interprets surface hodographs. A surface hodograph is represented on the surface of observations in the form of an isochrone map.

Construction of the isochrone maps. In the CMRW in area measurement with a single point of explosion, isochrone maps, which can be interpreted both qualitatively and quantitatively, are plotted. The isochrone maps are constructed in the following sequence: 1) a table is compiled of the times of arrival of the wave and all the corrections are introduced; 2) the times are interrelated at the points of intersection of the profiles in the way usually employed in topography; 3) the interrelated times of arrival of the waves are plotted in plan, and then the isolines of equal times - isochrones - are drawn; 4) the places of discontinuities in the correlation and the interchanges of the waves are noted by special symbols; in thse places the isochrones are broken.

The scales of the maps and the spacing of the isochrones depends on the extent to which the measurement is detailed. In the prospecting of small depths scales of 1 : 2,000 and 1 : 5,000 are used; the spacings used for the isochrones are 0.005 and 0.01 sec.

In prospecting at medium and large depths, the maps are plotted at 1 : 10,000 and 1 : 20,000 scales, and the isochrones are spaced 0.02 or 0.05 sec.

The form of the isochrones is determined, on the one hand, by the change in the distance from the point of ex-

plosion to the points of observation, and on the other hand by the changes in the relief of the refracting boundary and changes in the velocities V_1 and V_b. Assuming that V_1 and V_b are constant, it is possible, by excluding the influence of variation of the distance, to determine the relief of the refracting boundary.

The methods described below for the interpretation of the isochrone maps are based on the same assumptions regarding the structure of the medium and on the same methods of excluding the normal hodograph, as the method of interpretation of transverse profiles, discussed in the previous sections.

Elimination of the normal hodograph. As was done in Section 3, we shall call the normal surface hodograph the isochrone map plotted for the case of a horizontal separation boundary at constant velocities V_1 and V_b. Under these assumptions the isochrone map represents a system of arcs of concentric circles, the center of which is located at the point of explosion (Fig. 107). The distance Δl between the neighboring arcs is equal to $V_b \, \Delta t$, where Δt is the difference in markers between the neighboring isochrones, and V_b the velocity in the refracting layer. We shall henceforth call this map the normal field.

Calculating the normal field from the obsreved isochrone map, we obtain the difference in isochrone map Δt, the course of which is due only to the change in the depth of the refracting boundary.

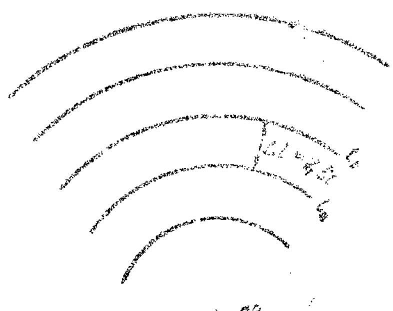

Fig. 107. Normal surface hodograph in the case of constant velocities V_1 and V_b.

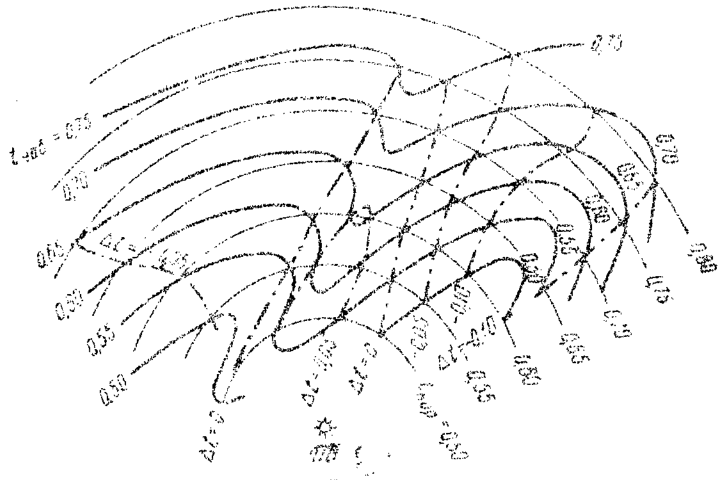

Fig. 108. Elimination of the normal surface hodograph t_{nor} from the observed hodograph t_{obs}. Thick lines - isochrones t_{obs}; thin lines - isochrones t_{nor}; dotted - isochrones of the difference hodograph Δt.

The substraction of the normal field is carried out graphically. The observed map of isochrones, traced on tracing cloth, is superimposed on the normal field. To construct the isochrones of the family Δt one finds the points of intersection of the isochrones t_{obs} and t_{nor}, the difference in the markers of which is $\Delta t = t_{obs} - t_{nor}$ and a constant quantity (Fig. 108). By joining the indicated points with a smooth curve, one obtains one of the isochrones of the family Δt. The entire family of the isochrones Δt is plotted in the same way.

Determination of the relief of the refracting boundary. To determine the variation in the thickness ΔH, it is necessary to multiply the resultant values of Δt, in accordance with formula (37), by the coefficient $V_1/\cos i_{12}$; the resultant values of ΔH are assigned to the isolines of the previously plotted map Δt. This map of isolines ΔH characterizes the relief of the refracting boundary with respect to the surface of observations, not interrelated with the absolute depths; the correlations for the drift in the construction of this map are disregarded. To construct the contour-line maps of the refracting boundary with allowance for the drift, it is necessary to know the

depth H_0 in the reference point of emergence. The construction of the contour-line map differs somewhat in the case when the surface of observations represents a horizontal plane, and in the case when this surface differs from the horizontal plane. Therefore, we shall consider separately the construction of the contour-line map for both cases.

Construction of the contour-line map of the refracting boundary in the case when the surface of observation is a horizontal plane. In this case the construction of the map of isohypses is carried out in the following manner.

1. Knowing the depth H_0, corresponding to one reference point of emergence, one calculates for each of the isolines ΔH the depths in accordance with the formula

$$H_k = H_0 + \delta(\Delta H),$$

where $\delta(\Delta H) = \Delta H_k - \Delta H_i$ is the difference in the markers of the isolines ΔH_k and ΔH_i, passing correspondingly through the arbitrary k-th point and through the i-th point with specified depth H_0. The values of the depths H_k calculated in this manner, are marked over the isolines of the map ΔH_k.

2. For each isoline with marker H one calculates the value of the drift in accordance with formula (40).

3. Each of the isolines H is shifted point by point in the direction towards the point of explosion by the magnitude of the drift (Fig. 109).

The map obtained in this manner represents a map of equal depths of the refracting boundary. In the case under consideration, when the surface of observations is a horizontal plane, the equal-depth map coincides in the form of the isolines with the map of isohypses. To change over to absolute markers it is enough to know the marker of the plane of observation.

The observation surface differs from a horizontal plane. To construct the contour-line map of the refracting boundary, it is necessary to have a contour-line map S_p of the surface P of observation and the map of equal depths H,

calculated by the method described for the case of a horizontal surface observation without allowance for the drift. The marker of each e-th point of the refracting boundary (Fig. 98) is determined from the relation

$$S_{eQ} = S_{kP} - H_i.$$

To construct the contour-line map in this case one can perform the following operations.

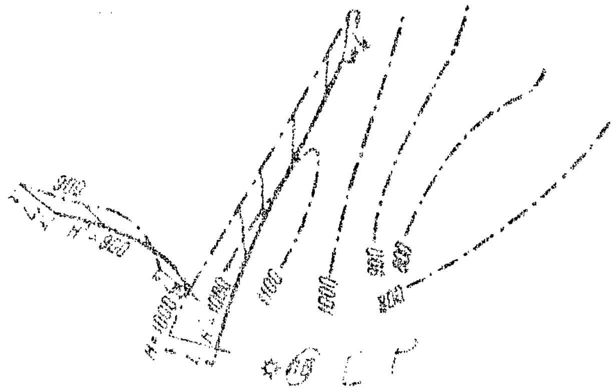

Fig. 109. Introduction of corrections for drift into the equal-depth map. Dotted lines - isolines of depth H without allowance for drift; solid lines - isolines of depth H' with allowance for drift.

1. As in the case of the horizontal surface of observation, for each isoline with marker H_k one calculates the value L_k of the drift and the value of L_k is marked on the isolines. Consequently, the map of equal depths H, constructed without allowance for the drift, is simultaneously the map of isolines L of the value of the drift.

2. A contour-line map S_Q is plotted without allowance for the drift. For this purpose one substracts graphically the map of equal depths H from the contour-line map S_P of the surface of observation. Through the points of intersection of the isolines S_P and H, the difference of markers of which represents a constant quality, one draws a smooth curve, which represents one of the isolines S_Q (Fig. 110). All the isolines of the family S_Q are constructed in the same manner.

3. On the map of isolines S_Q one superimposes the map of isolines of the magnitude L of the drifts, and at the points where the isolines S_Q and L intersect, the isolines S_Q are marked with the corresponding values of L of the drift (Fig. 111). Thus at different points of one and the same isoline S_Q the value of the drift is different.

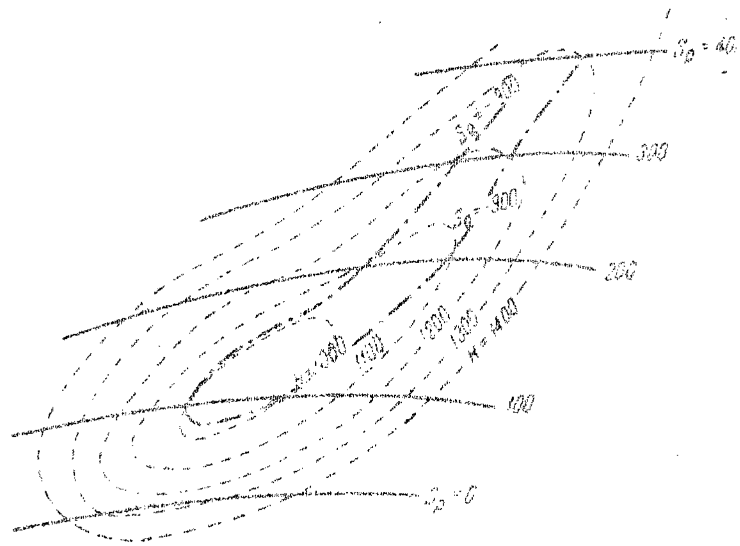

Fig. 110. Construction of the contour-line map S_Q without allowance for the drift in the presence of the surface relief. Solid lines - contour lines S_P of the surface of observations; dotted - isolines of the depth H (without allowance for the drift); dash-dot line - isoline S_Q.

4. Knowing the values of the drift at different points of any one isoline S_{IQ}, one shifts this isoline point by point in the direction towards the point of explosion (Fig. 111). Thus all the isolines are shifted. As a result of this construction, there is obtained a contour-line map S'_Q of the refracting surface with allowance for the drift.

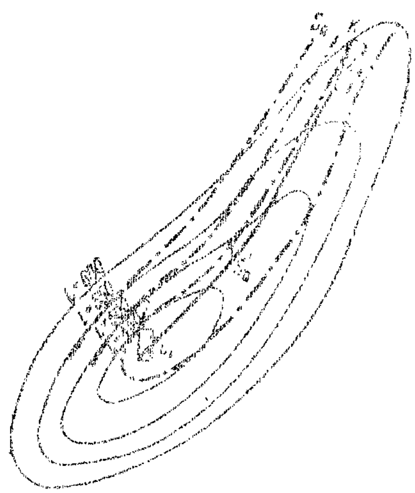

图 118

Fig. 111. Introduction of corrections for the drift on the contour-line map. Dash-dot line – isolines of S_g without allowance for the drift; thin continuous lines – isolines of the drift L; thick continuous lines – isoline S'_g, constructed with allowance for the drift.

Construction of the equal-depth map with allowance for the drift. For prospecting purposes one needs frequently, in addition to the contour-line map, also a map of equal depths of the refracting boundary, which in the case of a non-horizontal surface of observations differs from the contour-line map. To compile the map of equal depths with allowance of the drift it is enough to substract graphically the contour-line maps S'_g, constructed with allowance for the drifts, from the contour-line S_p of the surface of observation. The map obtained as a result of the substraction is the equal-depth map H' of the refracting boundary, constructed with allowance for the drift.

7. Interpretation of the Isochrone Maps in the Case of Multiply-Layered Media with Constant Velocities

In the case of a multiply-layer medium, consisting of relatively thick layers with different velocities of propa-

gation of elastic waves, as indicated in Section 5, it is nevessary to take into account in the interpretation also the refraction by the higher separation boundaries. For this purpose it is possible to use approximate methods, analogous to those considered in Section 5 for the transverse hodographs.

We give below a discussion of a method of interpretation in the case of two refracting boundaries. This method can be generalized for the case of an arbitrary number of separation boundaries.

Construction necessary for the interpretation of the isochrone map corresponding to the second refracting boundary. The isochrone maps t_1 and t_2 are given. It is assumed in the examination, as in Section 5, that the layer velocities V_1 and V_2 and the boundary velocities V_{b2} and V_{b3} are constant and specified.

For the construction of a contour-line map of the second refracting boundary it is necessary to perform intermediate operations, by constructing the following maps: 1) map of equal thicknesses H_2 of the second layer (without allowance for the drift); 2) map of equal depths $H = H_1 + H_2$ of the second refracting boundary (without allowance for the drift); 3) map of equal lines of the value L of the drift. Let us consider the methods of compiling the foregoing maps.

Construction of map of equal thicknesses H_2 (without allowance for the drift). For the compilation of this map one can use formula (50).

$$\Delta H_2 = (\Delta t_2 - k\Delta t_1)\frac{V_2}{\cos i_{23}},$$

where $k = \frac{\cos i_{13}}{\cos i_{12}}$, $i_{12} = \arcsin\frac{V_1}{V_{Г2}}$, $i_{13} = \arcsin\frac{V_1}{V_{Г3}}$ and $i_{23} = \sin^{-1}(V_2/V_{b3})$. Each of the quantities Δt_i ($i = 1, 2$) can be represented in the form of a difference of the observed quantity t_i from the corresponding normal field. Then the expression ΔH_2 assumes the following form

$$\Delta H_2 = \left[\left(t_2 - \frac{x}{V_{Г3}}\right) - k\left(t_1 - \frac{x}{V_{Г2}}\right)\right]\frac{V_2}{\cos i_{23}} = \left[(t_2 - kt_1) + \left(\frac{kx}{V_{Г2}} - \frac{x}{V_{Г3}}\right)\right]\frac{V_2}{\cos i_{23}} \quad (55)$$

The technique of constructing the map of equal thicknesses H_2 reduces to the following operations.

1. The markers of the isochrones of the observed isochrone map t_1 corresponding to the first refracting boundary, are multiplied by the factor $k = \frac{\cos i_{13}}{\cos i_{23}}$.

2. The map of differences $t_2 - kt_1$ is made up graphically. The method of compilation of the difference maps is indicated in Section 6.

3. A map of equal lines is constructed for the difference $kx/V_{b2} - x/V_{b3}$ of the normal field x/V_{b2}, corresponding to the first refracting boundary, multiplied by the constant factor, k, and the normal field x/V_{b3}, corresponding to the second refracting boundary. The construction is carried out in the following manner. Using the explosion point as a center, a family of circles is drawn representing a family of isochrones $\Delta t_{norm} = kx/V_{b3}$; the difference between two neighboring isochromes is equal to $\frac{\Delta t}{\frac{k}{V_{r2}} - \frac{1}{V_{r3}}}$ where Δt is the difference in the isochrone markers.

4. A map is constructed of

representing the result of the summation of the two difference maps, the construction of which is considered in items 2 and 3 above.

5. The markers of the isochrones of the map Δt are multiplied by the constant factor $V_2/\cos i_{23}$. The map obtained in this manner is the map of ΔH_2, the variation in the thickness of the second layer without allowance for the drift.

6. To change over to the absolute values of the thickness it is necessary to know the thickness H_{02} at one reference point. Knowing H_{02}, it is possible to replace the markers of the isolines ΔH_{2k} by markers $H_2 = H_{02} + \delta(\Delta H_2)$, where $\delta(\Delta H_2 = \Delta H_{2k} - \Delta H_{21}$ is the difference in markers of the isolines H_{2k} for which the value H_2 is determined, and the isolines ΔH_{21} passing through the reference point, for which the thickness is H_{02}.

All the operations of the compilation of the difference and summary maps are carried out graphically (see

Section 6), and consume little time. It must be noted that when k is close to unity, the operation indicated in item 1 is no longer necessary. In this case one makes up their difference map from the two observed maps of the isochrones t_1 and t_2 and the map of differences of two normal fields, corresponding to the two refracting boundaries, and this is followed by the operations indicated in items 4, 5, and 6.

<u>Construction of the map of equal depths of the second diffracting boundary (without allowance for drift).</u> To compile this map it is necessary to sum the maps of isolines H_1 and H_2, uncorrected for the drift, The summation can be carried out graphically.

<u>Construction of the contour-line map (without allowance for the drift).</u> If the surface of observations represents a horizontal plane, then to change over from the equal-depth map of the second refracting boundary to the contour-line map it is enough to replace the markers on the map of equal depths by the contour-line markers. If the surface of observation differs from the horizontal plane, then to compile the contour-line map of the refracting boundary it is necessary to have a contour-line map of the surface observations. The contour-line map of the refracting boundary is found by graphic substraction of the equal-depth map $H = H_1 + H_2$ from the contour-line map S_p of the surface of observations (Fig. 109).

<u>Construction of the map of equal drift lines L.</u> The corrections for the drifts are calculated by formula (52). Each isoline of the equal-thickness map H_2 corresponds to a constant value H_2 and i_{23}, and each isoline of the equal-depth map H_1 corresponds to a constant value $H_1 \tan i_{13}$. The constructed equal-drift maps are constructed in the following manner.

1) On each isoline of the equal-depth map H_1 we write out the quantities $H_1 \tan i_{13}$, and on the equal-thickness map H_2 we mark each isoline with the quantity $H_2 \tan i_{23}$.

2) A graphic summation is made of the maps of the isolines $H_1 \tan i_{13}$ and $H_2 \tan i_{23}$. This results in a map of isolines of the magnitude of the drift L.

<u>Introduction of corrections for the drift in the</u>

contour-line map. To introduce corrections for the drift in the contour-line map it is necessary to perform the following operations:

1. The contour-line map S_Q of the refracting boundary, constructed without allowance for the drift, must be superimposed on the isoline map of the drift L. At the points of intersection of the isolines S_Q with the isolines L it is necessary to write down the values of the drift, determined by the markers of the isoline L. Thus, at different points of one and the same isoline S_Q the value of the drifts L is different.

2. Knowing the values of the drift at different points of the isoline S_Q, this isoline is shifted point by point in the direction towards the point of explosion. The map plotted in this way represents the contour-line map S'_Q of the refracted boundary, corrected for the drift.

Construction of equal-depth maps of the refracting boundary with allowance for drift. In the case when the surface of observations differs from the horizontal plane, the construction of the equal-depth map with allowance for the drift can be carried out if a contour-line map S_Q has been plotted for the refracting boundary with allowance for the drift and a contour-line map S_P of the surface of observation is given. The construction is carried out by the same method as indicated in the preceding section.

Chapter VII

PROSPECTING CAPABILITIES OF THE CMRW

Prospecting problems resolved with the aid of the CMRW, used either independently or in combination with the method of reflected waves, can be evaluated primarily on the basis of more than ten years' experience in testing and application of this method in various seismogeological conditions of different regions of the USSR, where it was subjected to a great variety of problems.

Another source of evaluating the prospecting capabilities of the CMRW are the general physical considerations, based on experience and theory of the seismic method as a whole and partially on progress and development of neighboring fields of knowledge, particularly those sciences and branches of technology, which deal with wave processes (acoustics, optics, radio engineering, etc.). These considerations make it possible to foresee the capabilities of the CMRW in those fields, where this method is still not extensively used or not used at all.

We list below the capabilities of the CMRW primarily on the basis of data of the first kind, already tested in practice.

1. Investigation of a Crystalline Foundation

Investigation by means of the CMRW of the crystalline foundation, covered with a layer of sedimentation rocks, consists of determining its depth and the relief of its surface, and also a general velocity characteristic of the crystalline and metamorphic rocks, which form the foundation.

Prospecting at small and medium depths. The easiest problem for the CMRW in this field is the study of the position of the bed of the crystalline foundation at small depths -- from several meters approximately to one kilometer -- under conditions when the foundation is covered by layers of sandy-clay or other rocks with relatively small velocities of propagation of elastic waves. The velocity of the longitudinal elastic waves in the foundation is large, on the order of 5-6 km/sec and greater, which makes it possible to distinguish crystalline and metamorphic rocks of the foundation from the sand-clay rocks of the covering layer, which are characterized by small velocities. It has been noted that the refracted (frontal) waves, corresponding to the crystalline rocks, usually have a low intensity compared with the waves in sedimentation rocks, but on the other hand as the distance from the point of explosion increases they attenuate slowly with distance, and they therefore can be readily traced over a sufficient length of the profile.

A complicating circumstance in the prospecting of the bed of the foundation at small depths may be the presence of a contemporary or ancient weathering crust of surface portions of the foundation, the thickness of which may fluctuate from fractions of the meter to ten meters and above. The velocities of the elastic waves and this crust may also be of the same order as in the rocks of the sedimentation layer. This may lead to conclusions of a large depth of the foundation compared with the true one. As the depth of the foundation increases, greater absolute errors are allowed in its determination, and therefore the possible error due to the existence of the weathering crust loses its practical significance.

If the rocks in the covering layer contain "screening" layers of limestones or other rocks with high velocities of propagation of elastic waves, then the prospecting of the bed of the crystal foundation, as in general prospecting by the method of refracting waves (CMRW) at any depth and for any purpose may be difficult or even practically impossible, depending on the ratio of the thickness of the screen and the predominating length of the registered waves (see Chapter I, Section 1, and also /10/).

Prospecting of the bed of the crystal foundation at a small depth is carried out in the CMRW method principally with the aid of longitudinal profiles. As the depth increases, they are frequently supplemented by transverse profiles. The latter are used in particular in the study of features of the relief of the bed of the foundation, connected with tectonic disturbances (faults, etc.) or due to external causes (for example, erosion).

Prospecting of the crystalline base at a shallow depth of the base has been carried out successively with the aid of CMRW in many regions of the USSR.

<u>Prospecting at great depths</u>. The prospecting of the surface of crystal foundation, when they are located at great depths -- from one to four or five kilometers and deeper -- the basic premise indicated above remains in force: no difficulties are encountered in the prospecting in the absence of screens, and in their presence the question of the capabilities of the CMRW depends on the ratio of the thickness of the screen and the predominating length of the wave.

The features of prospecting of the foundation at greater depths, as in general of prospecting at great depths with the aid of the CMRW, consist of the necessity of registering refracted waves at large distances from the point of explosion. Thus, in one of the platform regions, where according to the CMRW data the foundation is located at a deoth of approximately 1.5 km, the corresponding refracted waves appear only at distances more than eight kilometers from the point of explosion, and immerge into the region of first arrivals at a distance of approximately ten kilometers from the point of explosion.

The greater distances are associated with an increase in the requirements imposed on the seismic effectiveness of the explosions and on the effective sensitivity of the apparatus.

In the case of observations at long lines (on the order of ten kilometers and above), it is most advantageous to carry out the explosions in water reservoirs, something that must be taken into account when choosing the place-

ment of the profiles. However, more frequently it is still necessary to make explosions in shot holes (and sometimes in excavations). In this connection, operations of this kind must be provided with sufficiently powerful drilling means: explosive shot holes, in view of the relatively large charges (up to five killograms and above), go rapidly out of order, and they must frequently be duplicated.

Sufficient effective sensitivity of the apparatus in observations over long lines is obtained by the means indicated in Chapter II and in Section 8 of Chapter III. We shall note here only the principal ones: change over to the registrations at lower frequencies.

In the prospecting of the bed of a crystal base at great depth, the references are the longitudinal profiles. To determine the special positions of this surface, the longitudinal profiles are accompanied by tranverse ones. To investigate structures - faults, etc. - one can use also area surveys with fixed positions of the point of explosion.

Successful work on the CMRW for the determination of the relief and depths of a crystalline foundation (and the separation of the sedimentation layer) at large and medium depths have been carried out in various regions of the USSR. Great difficulties in the solution of this problem were encountered in one of the regions of the Russian platform, in view of the presence of thick screens, but it was shown subsequently that these difficulties can be partially overcome by increasing the distance to the explosions.

The experience with the large number of investigations of the surface of a crystalline base for all depths has shown that the results obtained when this problem was solved with the aid of a CMRW, as regards uniqueness in the interpretation and accuracy, are usually superior to the data obtained by other geophysical methods, including seismic prospecting by the method of reflected waves.

In the method of reflections this surface does not obtain a velocity characteristic and can be mistaken for

can sometimes be obtained on the basis of a study of the degree of attenuation of the associated refracted waves with increasing distance from the point of explosion, and also by comparison of the CMRW data with the results of the determination of the average and layer velocities by means of seismic coring and by the method of reflected waves.

The procedure of operations in the CMRW in the breakdown of the sedimentation layer consists of passing over longitudinal profiles and obtaining on them, as a rule, detailed systems of opposite and overtaking hodographs with full correlation of at least the basic traced levels. The determination of the relief of the boundary is usually carried out also with the use of transverse profiles.

If the problem of the breakdown of the sedimentation layer is posed in order to obtain the most general representations of the seismogeological section in the region, then for large regions it is solved by carrying out individual seismic soundings by the CMRW. A comparison of the data by these separated observations, for the purpose of identifying the layers, is carried out principally on the basis of the analysis of the values of the boundary velocities and the dynamic features of the waves; one also takes into account the depth and the relief of the refracting boundaries. Naturally, the general geological ideas concerning the structure of the region are also taken into account.

In a more detailed investigation of the region, continuous profiling is used.

Operations on the breakdown of the sedimentation layer with the aid of the CMRW were carried out in the region of European and Asiatic portions of the USSR. In operations of this kind, the CMRW can be used in conjunction principally with the method of reflected waves (at medium and large depths) and with electric prospecting (essentially at small and medium depths). To interrelate the geophysical data with the geological ones, reference drillings are necessary, which should be accompanied by seismic carottage and seismic sounding by the CMRW and by the method of reflected waves.

3. Study of Structure in the Sedimentation Layer

In these problems, which are usually solved with the aid of the method of reflected waves (in the range of not too small depths), use has been made of the CMRW in the past years primarily in those cases when in the use of the reflected-wave method one encountered conditions which prevented its successful application.

Experimental operations in 1941-1943. The first attempt of using the CMRW in the solution of problems of this kind were the experimental investigations in the region of the Ishimbayskiy Priural' (Bashkir ASSR) in 1941-1943. In this region, work on the method of reflected waves was performed intensely, in large volume, but essentially unsuccessfully over the extent of many years, starting with 1934. The principal problem which was faced by seismic prospecting in this region, was of finding tectonic limestone uplifts, complicated with reef formations (Artinskiy limestones), covered with quite inhomogeneous layers of hydrochemical precipitates (Kungur), and then by layers of clay, and further by sand-clay and in places by gravel deposits. The velocities of the seismic waves in the limestones and in the covering hydrochemical rocks were approximately of the same order.

Work on the CMRW in this region has proved the possibility of using this method to solve certain particular prospecting problems, but the main problem still remained unsolved. Experience with this work has shown that under the conditions of the complex structure of the medium in depth, when using the CMRW, one can encounter difficulties of the same order as in the method of reflected waves, although the particular causes of these difficulties are not always the same.

In spite of the lack of substantial prospecting results, these investigations nevertheless yielded great methodological results and comprised an imporatnt stage in the history of development of the CMRW. The desire of overcoming the great difficulties has led to a detailed development of many very important problems in the proce-

dure and interpretation, and this contributed to a successful application of this method in other regions in subsequent years. Thus, detailed systems of observation were developed for longitudinal and non-longitudinal profiles, methods of area measurement, including with fixed point of explosion, and corresponding methods of interpretation; methods have been indicated of a qualitative analysis of the dynamic features of the waves.

It should be noted here that during the years elapsed since that time, the CMRW has become enriched with new apparatus and with many methodological and interpretation measures, the application of which will at the present time perhaps permit under difficult conditions to attain better prospecting results.

<u>Prospecting of structures in sand-clay deposits.</u> The capabilities of the CMRW in this region were investigated in 1944 in experimental investigations carried out in the Azerbaydzhan SSR [27]. The prospecting problem consisted of tracing the depth structure in a layer of sand-clay deposits of tertiary age. The depth of the prospected layers amounted to four kilometers or more.

Observations with the CMRW were carried out in zones which were previously called "blind", in view of the fact that in the use of the method of reflected waves one encountered here great difficulties. The latter were due to the peculiar structure of the upper layers, contributing to the production of intense seismic vibrations, which propagated along the surface of the soil with velocities of less than one kilometer per second and frequently arrived simultaneously with the reflected waves and interferred with their tracing. Observations have shown that the deep refracted waves always arrive ahead of these oscillations; furthermore, the latter usually damped at those distances, where the investigated refractions are being traced. Thus, these oscillations did not act as interference in the method of refracted waves.

The most complete data were obtained on the CMRW in these investigations for a layer close to the bed of Pontiac clay, located in a region of investigations at a depth of approximately three-four kilometers. In places

there were observed angles of inclination of this layer up to 30° and more (on transverse profiles). A comparison, where possible, of the results of the determination of the depths and the relief of this layer with the results of drilling and the method of reflections has shown a satisfactory agreement between the data obtained by the different methods.

In subsequent years, the CMRW was used in analogous problems in another region of Azerbaydzhan, where clear reflections could also not be obtained. The refracting boundaries were separated here at different depths up to two kilometers, but they were traced only at small intervals, so that it was impossible to disclose the geological structure of the section with sufficient completeness. The rea son for this, one must assume, was the excessive complexity of the structure of the medium in depth, rather than unfavorable surface conditions.

In another place, the reflected waves could not be registered at large areas covered with thick layers of gravel deposisits. Prospecting by the CMRW has made it possible to trace successfully in these zones, which were "blind" for the method of reflections, refracting boundaries at depths up to 2.5 kilometers. The prospecting results agreed with the general geological represnetations on the structure of the region. The procedure of observations by the CMRW in this region consisted, in principle, of passing along the longitudinal and particularly transverse profiles with placement of the seismographs within the confines of the "blind zone", while the points of explosion were located outside the zones, in places where the conditions of excitation of oscillations were favorable.

The experience of the operations in Azerbaydzhan has shown the possibility of observing, with the aid of the CMRW, refracting boundaries and of studying the structures under conditions of relatively weak lithological differentiation of the section, where the method of first arrivals could not lead to favorable results for some reasons. This experience has shown that no a priori statement can be made concerning the inapplicability of the CMRW for the study of structures in view, so to speak, of the absence

of refracting boundaries, based on data of the first arrivals, seismic coring, and the method of reflected waves, can be considered as convincing. The question of the applicability of the CMRW under such conditions can be solved only by setting up field observations precisely by the CMRW.

Prospecting of structures in carbonate deposits and in other dense rocks. Experience of operations under platform conditions has shown the possibility of separating, by means of the CMRW, of refracting boundaries in thick layers of limestones and dolomites and of tracing the relief of these boundaries.

In one of the regions of the Russian platform, in spite of the relatively homogeneous lithological composition of the rocks in a layer of limestones and dolomites of the carbon and Devonian age, it was possible to separate in this layer and to trace the relief of several refracting layers with nearly equal boundary velocities. In another region in a layer of hydrochemical deposits of Kungur and an underlying thick layer of carbonate rocks of the carbon age, where the velocity differentiation is very small, there were observed well traced refracted waves with clearly pronounced dynamic features, which made it possible to construct several of the refracting boundaries at different depths.

Prospecting of structures at small depths. The region of small depths (on the order up to 200 meters and frequently deeper) is as a rule inaccessible to the method of reflected waves in its ordinary modern form. This region is readily accessible for the CMRW.

The prospecting of structural forms for surface ancient erosion in layers located at small depths, on the order of tens or several hundreds of meters, were carried out with the CMRW in the coal basin near Moscow, in Kuzbass, and in Donbass. In one of the regions of the Kuzbass, the principal prospected boundary was a bed of Permian deposits, in which the velocity of propagation of elastic waves amounts to approximately three km/sec, whereas in the covering Jurassic sand-clay deposits, where layers of sandstone are encountered, one observes velocities of 2.5

km/sec, and sometimes even greater.

<u>Prospecting of structures under conditions of sharp lithological differentiation of rocks</u>. The prospecting of boundaries on which the lithological composition of the rocks (and therefore the velocity of propagation of elastic waves) changes sharply and strongly, with the velocities in the deeper layers greater than in the covering ones - this is the most studied application of the method of refracted waves even in its older form, the method of first arrivals. With the aid of the CMRW such prospecting can be carried out with considerably greater detail and accuracy.

Among the structures in the sedimentation layer, characterized by the foregoing conditions, one should note above all the salt-dome structures: the velocity in salt is approximately 4.5 km/sec, and in the covering sand-clay deposits it is up to three km/sec or somewhat greater. In addition to the obvious problem of tracing the relief of the salt core in the region of the vault of the dome, it is the task of the CMRW to investigate the relief and the velocity characteristic of the layers in the sand-clay layer, and particularly in the part near the vault, and the solution of such difficult problems as establishment of the contours of the layers in connection with the tapering of these layers, faults, the determination of amplitudes of the faults, etc. (see also Section 4).

In addition to the usual seismic prospecting with explosions at small depths, one can carry out with the aid of the CMRW also the prospecting with explosions in deep shot holes (seismic torpedos), with the seismographs located along the profiles on the surface of the earth, when the refracting boundary is prospected "by transmission." It is possible to investigate in this manner, in particular, the steeply descending walls of the salt shoots.

One encounters a sufficiently sharp differentiation of rocks by elastic properties and respectively by velocities in the case of seismic prospecting of structures in sedimentation deposits in the region of the Belorussian SSR. The CMRW is used here with great success, while

attempts at using the method of reflected waves frequently do not lead to satisfactory results owing to the unfavorable surface conditions (sands, floating earth, etc.).

An important auxiliary problem, which usually is resolved by the method of refracted waves, is the determination of the relief of strongly refracting boundaries in the covering medium, in order to take into account the refraction of waves by these boundaries in seismic prospecting of deeper boundaries. One deals with such a problem, for example, in the prospecting by the method of reflected waves of structures in Bashkiriya and Tatariya, where the boundary between the layers of hydrochemical deposits of the Kungur layer with a velocity near 5.5 km/sec, and the covering sand-clay deposit of the Ufimskiy and Kazan layers, with velocities near 2.5 km/sec, is found to be highly refracting. The accuracy with which this boundary was previously determined by the method of first arrivals is obviously inadequate, taking into account the high accuracy with which it is necessary to construct the reflecting boundaries for the disclosure of structures in deep layers, which are characterized here by small amplitudes with small angles of inclination of the skirts. In order to study the relief of this boundary (and also in order to study the distribution of velocities in the higher layers) one can and should use the CMRW. Problems of this kind should be solved with the aid of the CMRW also in other regions.

Let us proceed to make a few remarks on the procedure of operations with the CMRW in the study of structures in a sedimentation layer.

In structural prospecting at small depths, the observations are carried out essentially with the aid of longitudinal profiles, networks of which are made up in the detailed prospecting. At medium (hundreds of meters) and large (kilometers) depths, of investigation, one uses reference longitudinal profiles with a system of interrelated non-longitudinal profiles. At large regions of traceability of the refracted waves, corresponding to the investigated boundaries, one can also carry out area surveys in individual sections with the aid of networks of non-longitudinal profiles at a fixed position of the point of

explosion.

A specific feature of the procedure of prospecting at small velocity differentiation of layers, when the refracted waves form greater zones of mutual interference, and the regions of traceability of the individual waves in pure form are greatly shortened, is the application of relatively small distances between the points of explosion for the construction of total correlation systems of observations on longitudinal profiles. Such complete systems are usually constructed only for those boundaries, which are of principal prospecting interest.

It must be emphasized that searches in prospecting for structures in sedimentation layers with application of the CMRW can be carried out not only as a substitute for the method of reflections, where the latter cannot be used, but also to assist this method in those places where the application of the two methods can accelerate the seismic prospecting and improve its results. The problem of the specific purposes and forms of a joint application of the CMRW and the method of reflected waves is discussed specially in Chapter IX.

Work on the CMRW for the foregoing purposes can be carried out also in conjunction with other geophysical methods: in prospecting at small depths, principally with electric prospecting with direct current, and at large depths - with gravimetry.

4. Prospecting of the Separation Boundary Close to Vertical

Here we consider the following problems: the tracing over the area, the determination of the depths and vertical amplitudes of tectonic disturbances - faults, etc., which lead to a cessation of the existence of the investigated layer at a given depth and to its appearance at a different depth; next we investigate steep ledges or steps of similar character (in the geometric relation), but which will be the result of diapeirism of magnetic activity (shoots, in particular salt), or the result of folding

(flexure) or erosion etc.; next we investigate the lines of boundaries of layers close to horizontal ones, formed by tapering of these layers as a result of their immergence on the surface of the erosion under the "alluvia;" finally, the mapping of a series of steeply descending layers, the overall surface of erosion of which is hidden under approximately horizontal sediments.

Problems of this kind frequently involve considerable difficulties in seismic prospecting. In the method of reflected waves, the places of such disturbances are fixed most frequently as zones of absence of reflections, which is not always a reliable criterion, since clear reflections may not be obtained also for other reasons. With this, the method of reflections does not permit prospecting such structures at small depths. The possibilities of solving these problems with the aid of the CMRW are as follows.

Prospecting of steps and tapering layers. In the use of the CMRW and different regions it was frequently necessary to deal with steps (faults, steep local drops in the refracting layers) and tapering layers.

This made it possible to ascertain experimentally the possibility of investigating structures of this kind. We note that in prospecting by the method of reflected waves, particularly when the interpretation is by means of constructing the arbitrary levels, such structures are difficult to disclose and more so to prospect in detail.

In the case of steps, the task of the CMRW is to trace the position of the upper edge of the step in plan and to determine the amplitude of the step. The latter is carried out essentially by comparing the values of the boundary velocities for the investigated levels at sections with the raised layer deposits, and on the other hand with those having the dropped layers. The method of reflected waves cannot be employed in principle in this type of solution, for the boundary velocities cannot be determined by this method.

In the case of the tapering layer, the CMRW may be called upon to trace in plan the contour of the region where

the layer exists, and to determine the depth of this layer. The layer should have a higher velocity of propagation of elastic waves.

Problems of this kind, as is well known, were frequently solved earlier by the method of first arrivals. The CMRW makes it possible to solve them with great accuracy, detail, and with smaller limitations with respect to the structure of the medium and the properties of the rocks.

By way of an example of a successful prospecting of these structures for shallow layers one can indicate the case, described in the article [35], of the tracing of a contour of a location of a layer of limestones of thickness 8-10 meters, dropping to zero in the region where the layer tapers as a result of erosion. This layer was located at depths of 0.5-10 meters under a cover of Morainic deposits and was underlined with sand-clay rocks.

In Belorussia and other regions one encounters faults or steep step-like drops of layers at medium depths, on the order of hundreds of meters or a kilometer, when the refracting layers and the covering media have sharply different elastic properties.

Finally, an example of detection of a steep ledge at great depths, approximately three-four kilometers, when both the refracting layers and the covering medium were represented by sand-clay deposits, were obtained in CMRW investigations in Azerbaydzhan as early as in 1944.

The procedure of work with the CMRW on the investigation of steps and on tapering of layers consist primarily of passing along the longitudinal profiles across the line of the fault or of the contour of the tapering layer. With this, a brighter picture of the waves, evidencing the presence of the disturbance (diffracted waves), is obtained when the point of explosion is located over the raised skirt (see Chapter IV, Section 10, and also Chapter VI, Section 6). The line of fault can be traced with the aid of trabsverse profiles, located across this line. It is possible to make area measurements with a fixed point of explosion. To obtain more accurate values for the amplitude of the fault and for the values of the boundary

velocities near the point of disturbance, it is advisable to pass along the longitudinal profiles on the raised and on the dropped skirts, parallel to the fault line.

Prospecting for the series of steeply-descending layers. With the aid of the CMRW it is possible to carry out underground mapping of steeply-descending layers on the basis of the erosion surface of such layers, located under a cover of sand-clay deposits. One must deal with such a problem, for example, in the region of the Kursk magnetic anomaly.

The capabilities of the CMRW are determined in this region essentially by two circumstances. Firstly, this method makes it possible to distinguish rocks by the propagation velocities of the seismic waves; secondly, there are related to the steeply-descending separation boundaries of the layers characteristic seismic waves, pertaining to the refracted and diffracted waves, and the study of these makes it possible to delineate the boundaries of the regions of the extent of the rocks with different properties.

The horizontal thickness of steeply-descending layers should in this case be sufficiently large: usually on the order of the thickness of the covering layer and greater; also important are the wave langths (and respectively the frequencies) used in the prospecting.

The prospecting is carried out by a system of longitudinal and transverse profiles. The longitudinal profiles are specified trabsverse to the extent of the layers in order to observe the boundaries between them and to determine the velocities of the propagation of the waves in these layers in the transverse direction, and also along the extent of the layers, in order to determine the boundary velocities in the longitudinal direction. Either velocities are frequently quite different as a result of the thin stratification inside of the investigated layers themselves (quasi-anisotropy [56]). The transverse profiles are specified across the direction of the layers in order to determine the boundaries between layers.

The prospecting of variegated structures, listed in this section, can be carried out by the CMRW, depending

on the circumstances, in conjunction with one or several of the other geophysical methods, namely: magnetometry and gravimetry in the investigation of lines of large disturbances, particularly at great depths; with the method of reflected waves, particularly in the regions of salt-dome tectonics; with electric prospecting, principally in the investigation of the tapering of layers and faults at small depths; with the magnetic and gravitational variometry in studying a series of steeply-descending layers under "alluvia."

5. Prospecting in Special Conditions

Prospecting at small depths. Among the many problems which can be assigned to the CMRW in this region we note the following: the determination of the thickness of alluvia, consisting of loose rocks, under crustal rocks, which are denser; separation of fault zones; increased cracking of crustal rocks under alluvia; establishment of the position of the level of ground waters.

Problems of this kind have particular significance in engineering geology and hydrogeology.

The procedure of prospecting small depths for the foregoing purpose consists of passing essentially along longitudinal profiles.

Instead of using explosions, one sometimes excites the oscillations by means of impacts; it is possible to investigate with their aid layers at depths up to 20-30 meters.

A feature of seismic prospecting at small depths is the increase of the registered oscillation frequencies.

Features of marine prospecting. In seismic prospecting under the bottom of a shallow sea, with the water depth reaching up to several tens of meters, the presence of a layer of water is associated with the following principal singularities: a) in explosions in water there may be produced repeated impacts, which at ordinary charges and

depths of the charges follow approximately up to 0.1 sec and more after the explosion itself (see Chapter III, Section 6); b) associated with the bottom of the sea are intense low-frequency "bottom" waves, analogous to surface waves in dry land, propagating with small velocities; the influence of these waves on the recordings of the seismic oscillation can be readily excluded by using a corresponding frequency filtration of the oscillations in the apparatus; c) in the water there may be produced the so-called "seismic reverberation oscillations", connected principally with unevenness in the bottom; these oscillations propagate in a water layer with a velocity of approximately 1.5 km/sec (velocity of sound in the water), and are characterized by a broad spectrum of frequencies and frequently with very large intensities; if the bottom deposits absorb weakly the elastic energy, then these oscillations are weakly damped in time and in space, in view of the negligibly small absorption of sound in the water.

All these circumstances, and principally also the seismic reverberation, make the marine seismic prospecting more complicated, and at certain sections with particularly intense reverberation noise they make prospecting by the method of reflected waves practically impossible.

Experiments with the CMRW, carried out at the shores of the Caspian Sea on a small scale as early as in 1943, have shown that the refracted waves in marine observations have the same character as on land.

The important advantage of the CMRW over the method of reflected waves in prospecting in the zones of reverberation lies in the fact that the reverberation oscillations, which propagate relatively slowly, arrive as a rule considerably later than the traced refracted waves. In view of these, they cannot serve as interference in prospecting by the CMRW [27].

As regards repeated impacts, the follwoing can be said. These impacts can make it quite difficult to interpret correctly the recordings by the method of reflected waves, in connection with the fact that the reflected waves are always separated in the region of successive arrivals on the seismograms and have approximately parallel hodographs.

The reflections due to the repeated shocks may be erroneously assumed as reflections due to the explosion itself, but connected with deeper separation boundaries. The very fact of the existence of repeated impacts can sometimes be established with difficulty by means of only the form of the seismograms obtained in the usual technique of operations by the method of reflected waves, in view of the extensive utilization of automatic amplitude regulation. The latter distorts particularly strongly the form of the recording in the initial portion of the seismograph, soon after the first arrivals, when the repeated impacts could be most easily noted. Concerning the presence of repeated impacts one can judge on the basis of indirect data: the fact that the shape of the oscillations does not remain the same on the repeated records at one and the same points, but such a phenomenon may be due also to other causes.

In working with the CMRW no amplitude regulator is used, as a rule (Chapter II). This makes it possible to detect repeated impacts in a more direct manner - by the form of the recording on one end of the same seismogram. It is then easier to take them into account in the interpretation. If the refracted waves are traced in the region of the first arrivals, then the presence of repeated impacts does not influence at all the results of the interpretation. However, if the refracted waves are traced in the next portion of the seismogram, where the influence of the repeated impacts can appear, then the decoding of their recordings is still made easy by the fact that the refracted waves, connected with the different boundaries, usually have different apparent velocities, whereas the refracted waves, connected with one and the same boundary, but due to an explosion and repeated impacts, have identical apparent velocities.

The main principal capabilities of the CMRW in prospecting at sea remain the same as on land.

Depth sounding of the earth's crust. Experience of recent years has shown that with the aid of the CMRW one can sound the earth's crust at a depth of several tens of kilometers (up to 50 kilometers and more). When the method of reflected waves is used for this purpose in regions where

the crystalline foundation is covered by a thick layer of horizontally stratified sedimentation formations, a difficulty is encountered at first, due to the arising multiply reflected waves in the layers of the sedimentation cover, which may mask the reflections that arrive from inside the earth's crust. A stratified medium covering the crystal foundation may be "little transparent" for depth reflections, at least for oscillations at those frequencies (from ten cycles and above) with which the investigations have been carried out. However, in places where the crystal rocks immerge directly on the surface of the earth, no clear depth reflections have yet been observed.

In the case of deep sounding of the earth's crust by means of refracted waves (CMRW) it is necessary to register the oscillations at distances on the order of several hundreds of kilometers from the point of explosion. At such large distances the high frequency oscillations are rapidly attenuated, and consequently for deep sounding one uses lower frequency than in ordinary seismic prospecting.

The explosions are made in natural water reservoirs. Charges ranging from several tens to hundred and more kilograms of explosives of the ordinary type are used. We note that prior to the application of the CMRW, the registration of seismic waves, produced by artificial sources at such large distances was possible only by using high commercial explosives, where hundreds and thousands of tons of explosive matter were exploded simultaneously.

The correlation methods of registration of waves are now being used also in "large scale" seismology in the study of waves produced by natural earthquakes.

Thus, in the region of deep sounding of the earth's crust and the study of internal portions of the earth, the methods of seismic prospecting are related directly, by means of the CMRW, with the latest methods of the science of earthquakes, developed in the Soviet Union.

Chapter VIII

COMPARISON OF THE CMRW WITH OTHER SEISMIC METHODS

At the present time in the practice of seismic prospecting the most widely used is the method of reflected waves. Recently the CMRW began to be used. The method of first arrivals, which was developed earlier than other seismic methods, is still being used, but rarely; it clearly does not correspond to the modern level of development of knowledge and technology and is dying out, being replaced by the CMRW.

We give below a comparison of the CMRW with the method of first arrivals and with the method of reflected waves. The purpose of the comparison is the clarification of the place that the CMRW should occupy among the other methods of seismic prospecting.

1. Comparison of the CMRW with the Method of First Arrivals

The CMRW and the method of first arrivals are based on the registration of waves of one and the same type - on the registration of refracted or frontal waves (see Chapter I).

Separation and tracing of the waves. The separation and tracing of the waves in these two methods is based on different principles. In the CMRW the waves are separated and traced in the region of first arrivals and in the region of subsequent arrivals, on the basis of the principles of phase correlation. With this, one takes into account all the singularities of the shape of the recor-

ding, the intensity of the wave, the apparent velocity, and the in-phase relationship of the oscillations. Such a tracing makes it possible to investigate in detail the behavior of individual waves and to separate replacement of waves most reliably by means of the seismograms. The procedure of observations, used in the CMRW, insures the possibility of directly tracing the waves along the line of observations or over an area.

In the method of first arrivals one notes on the seismograms the barely noticeable moments of the start of the oscillations, which are assumed to be the arrivals of the waves. The only quantity which characterizes the wave is the time of its arrival. The separation of the individual waves is carried out by the hodographs; the principal criterion in this case is the presence of breaks in the hodgraph, due to the changes in the apparent velocities.

In the decoding of the hodographs of the first arrivals it is frequently difficult to solve uniquely the problem of the cause of the break in the hodographs, whether it is caused by the arrival of a new wave, corresponding to a deeper layer with a greater velocity, or whether it corresponds to a change in the angle of inclination of one and the same separation boundary.

The registration of waves in the region of subsequent arrivals, which is carried out in works on the CMRW, makes it possible to establish uniquely the cause of the break in the hodograph by means of an analysis of the character of the transition of the first waves into the region of subsequent arrivals. If one passes after the point of the break in the wave from the region of first arrivals into the region of subsequent arrivals and one traces in this region over considerable distances, this indicates the arrival of a new wave, corresponding to a deeper separation boundary. But if the oscillations on both sides of the point of break are traced only in the region of the first arrivals, or at a very small interval in the region of the successive arrivals, and the shape of the recording upon going through the point of the break, does not change, this indicates a change in the angle of inclination of the same separation boundary.

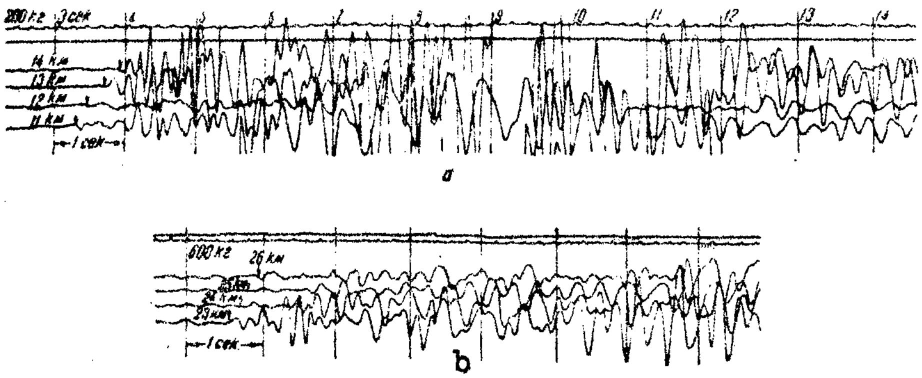

Fig. 112. Seismograms obtained working with the method of first arrivals [41]: a - at r = 11 - 14 kilometers, Q = 200 kilograms; b at r = 23-26 kilometers, Q = 600 kilograms. The arrows indicate the first arrivals.

kr - kg
cek - sec
km - km

Registration of the first arrivals. An examination of the materials obtained with the aid of the method of first arrivals shows that the separation of the actual first arrivals of the waves on the recording is in the overwhelming majority of cases exceedingly difficult or impossible. In view of the damping of the oscillations with distance, it becomes possible to separate on the recordings only certain subsequent phases of oscillations, which are sufficiently weak in intensity. These visible starts of the recordings were indeed taken as a first arrival. Fig. 112 shows seismograms obtained in working by the method of first arrival in 1941 [41].

In investigations based on the method of first arrivals with the aid of the apparatus used in the method of reflected waves, the separation of the first arrivals of the waves is even more difficult. The higher-frequency

components of the oscillations, produced by the explosion, for the registration of which the apparatus of the method of reflected waves is tuned, are attenuated with distance more rapidly than the low-frequency components, and the separation of the arrivals of the waves on the recordings becomes impossible as a rule. Only at very small distances from the point of explosion is it possible to separate the first arrivals of the waves. The separation of the later phases of the oscillation instead of the true first arrivals of the instants of registration should result in errors in the interpretation of the materials.

It must be noted that the tracing of the first arrivals is not excluded when working with the CMRW, but is a component part of this method, whereas the tracing of the first waves by methods used in the CMRW can be carried out much more reliably with allowance of the singularities of the form of the recordings in the initial portion of the seismogram.

The correlation tracing of the waves makes it possible to carry out a correct tracing of the phases of the oscillations and, by introducing corrections for the first arrivals, to correlate the observed data with the first arrivals.

Regions of traceability of the waves. The regions of traceability of each individual wave are small in the method of first arrivals as compared to the CMRW. In the CMRW it is possible to trace waves in the region of successive arrivals before and after the emergence of the wave into the region of the first arrivals and after the transition of the wave from the region of first arrivals into the region of succeding arrivals. When working by the method of first arrivals, the wave can be traced only in that portion, where it is registered as first.

Fig. 113 shows a schematic hodograph for a medium with two refracting boundaries. The wave t_2, corresponding to the boundary (2), is traced in the region of first arrivals in the section CD. When tracing the wave in the regions of both the first and subsequent arrivals, the separation of the wave t_2 is possible over a considerably

greater section from the point A to a certain point E, where the wave t_2 is damped out or else its tracing becomes impossible for some other causes (interference with other waves, etc.).

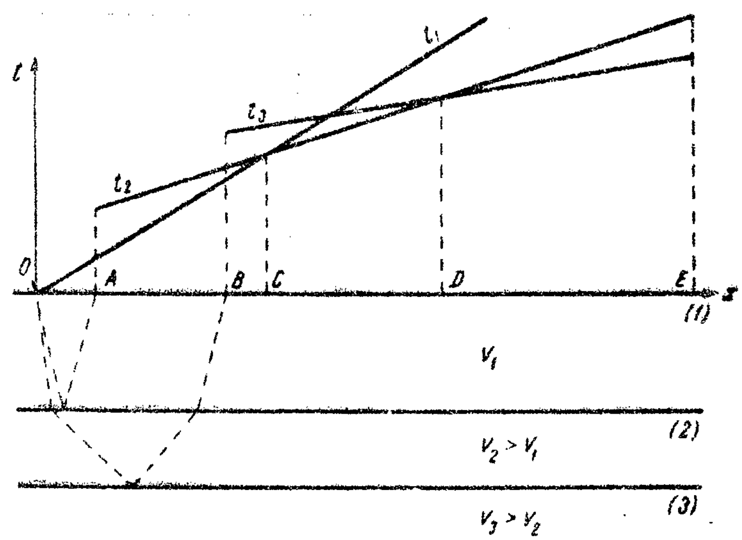

Fig. 113. Schematic hodographs of refracted waves for a three-layer medium.

Fig. 114 shows hodographs obtained in investigations by means of the CMRW. The wave t_B can be traced in the region of successive arrivals starting with a distance on the order of r = 4 km from the explosion point, and in the region of first arrivals it immerges only at a distance of r = approximately 13 km.

<u>Number of traced waves</u>. In the method of first arrivals in each of the profile it is possible to separate only one wave, registered as the first wave. In the CMRW and one and the same section of the profile one can trace simultaneously several waves, corresponding to different separation boundaries: one of these waves is registered as

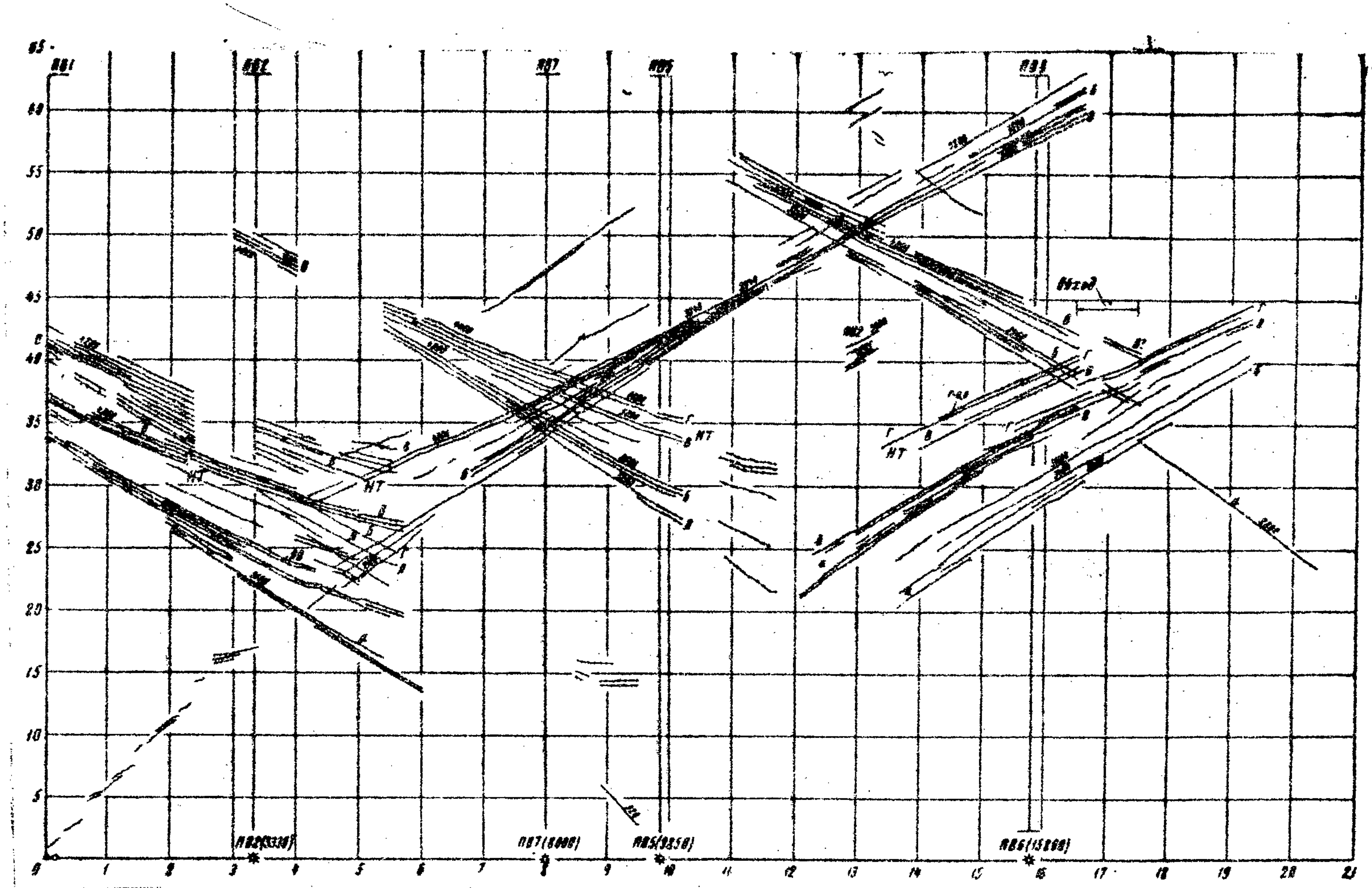

Fig. 114. Hodographs obtained in investigations by means of the CMRW. The ordinates represent the time in tenths of a second.

HT - IP (initial point), ПВ - EP (explosion point).

first, and all the others are registered in the region of successive arrivals. This makes it possible to carry out a more complete study of the medium. On Fig. 115 is shown a hodograph by the CMRW, showing that in the section r = 700-900 at point of explosion 490, there have been traced simultaneously the waves t_1, t_3, t_4, t_5 whereas the method of first arrivals would make it possible to separate in the same section only the wave t_1.

Procedure of observations. The possibility of tracing waves in the region of subsequent arrivals and consequently the possibility of simultaneously tracing several waves in one and the same section, makes the CMRW methodologically superior to the method of first arrivals.

The registration of succeeding arrivals makes it possible to reduce the length of the profile, to reduce the volume of work, and to reduce the cost of the work. By way of an example, let us consider the schemes of observations for investigating the separation boundary, corresponding to the refracted waves, appearing in the region of successive arrivals at a distance r = 4 km from the point of explosion, and emerging in the region of first arrivals at r = 13 km. Assume it is required to plot the separation boundary in a scetion approximately 20 kilometers long. When working with the aid of the CMRW, this can be realized by setting up a system of observations at maximum distances of the order of 10 kilometers from the explosion point. When working with the method of first arrivals, maximum distances on the order of 25 kilometers are necessary. The possible schemes of observations for tracing the refracted waves in the CMRW and in the method of first arrivals are shown in Fig. 116.

Range of reception. To separate the first arrivals it is necessary to obtain more intense recordings than to separate the phases of the same waves. Therefore, for a given type of apparatus, regardless of the type, the reception range should always be greater when tracing the phases of the oscillations then when tracing only the first arrivals.

When working with the CMRW it is enough to obtain o individual more favorable sections (close to the point of

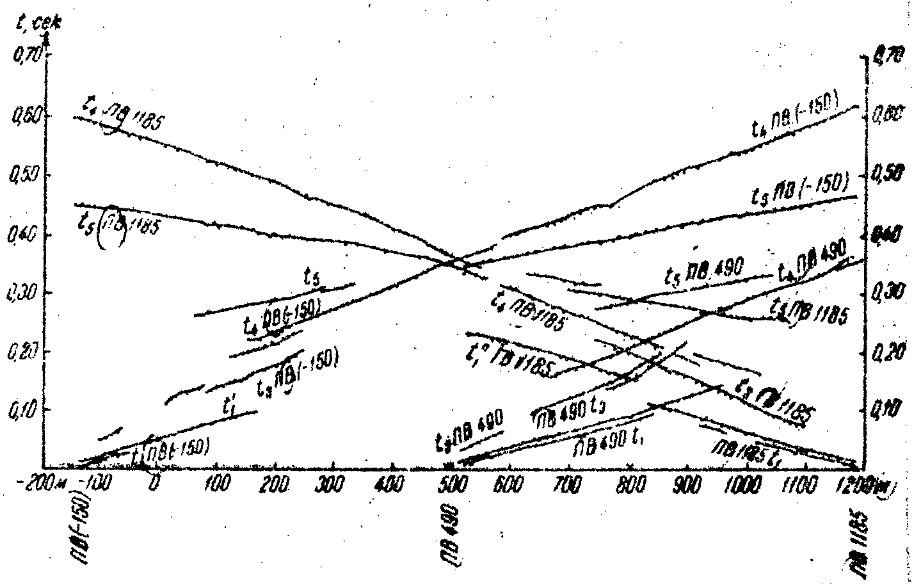

Fig 115. Hodographs of refracted waves, obtained by the CMRW. [ПВ = EP]

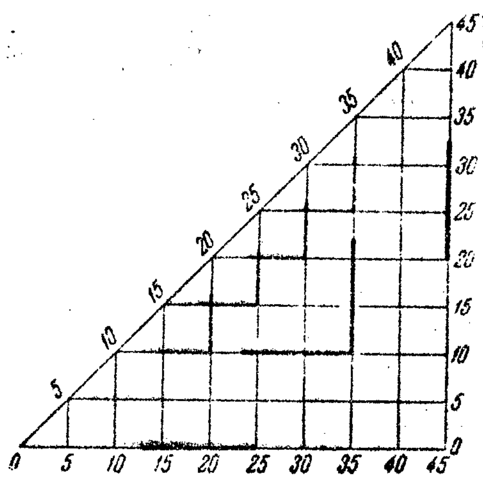

Fig. 116. Schemes of observations by the CMRW and by the method of first arrivals. Thin lines - by the CMRW, thick lines - by the method of first arrivals.

explosion, free of noise, etc.) an intense recording of a given wave, to determine from this recording the correction for the first arrivals, and to introduce this correction into the hodographs of the phases. In the method of first arrivals it is necessary to obtain systematically, along the entire profile, recordings of the first arrivals of the waves, and this requires large charges.

If we compare the reception range in the method of first arrivals in the version used during prospecting (i. e., where one uses mechanical, capacitive, and microphone types of seismographs) with the CMRW (where modern apparatus is used) we see the CMRW affords a considerably greater reception range than the method of first arrivals. Certain data on the magnitudes of the charges, used in investigations with the CMRW and with the method of first arrivals at different ranges from the point of explosion are given in Table 9.

Table 9

1) Метод первых вступлений				2) КМПВ			
3) Район и год работы	4 Аппаратура	5 Расстояние в км	6 Заряд в кг	3 Район и год работы	4 Аппаратура	5 Расстояние в км	6 Заряд в кг
7) Сев. Кавказ, 1928	9) Сейсм. механ. типа	0,5—1	15	11) Башкирия, 1950	13) Сейсмич. станция (37 гц)	4,5	0,05
		2—3,5	45			8	0,3
		4—7	240	12) Владимирская обл., 1940	14) Сейсмич. станция (40—50 гц)	32	5
8) Калужская обл., 1941	10) Сейсм. емкостного типа	11—14 23—26	200 600	11) Башкирия, 1950	15) Сейсмич. станция (10 гц)	23	27

1) Method of first arrivals
2) CMRW
3) Region and year
4) Apparatus
5) Distance in kilometers
6) Charge in kilograms
7) Northern Caucasus, 1928
8) Kaluzhskaya Oblast, 1941
9) Mechanical seismograph
10) Capacitive seismograph
11) Bashkiria, 1950
12) Vladimirskaya Oblast, 1940
13) Seismic station (37 cycles)
14) Seismic station (40-50 cycles)
15) Seismic station (10 cycles)

<u>Study of the separation boundary in those cases, when the corresponding refracted waves are not registered as fist waves</u>. The two following cases are possible.

a) When the velocity in the refracting layer is greater than the velocities in all the higher medium, and at definite ratios of velocities and depths of the different refracting layers, the waves corresponding to a certain separation boundary may not be registered as first waves. In the method of first arrivals this case is called the method of dropping out of the layers [14,23]. A study of such layers with the aid of the method of first arrivals is impossible. In the CMRW this study represents no principal difficulties, since the wave can be traced in the region of successive arrivals.

b) If the velocity in the layer is less than the velocity at least in one of the higher layers, or is equal to it, the so-called phenomenon of screening will take place [10].

The method of first arrivals does not permit, in principle, solving the problems connected with the study of behavior of the separation boundary located below the screening layers, since the waves corresponding to these separation boundaries are not registered in the region of first arrivals.

Experimental and theoretical investigations have shown that when the layer with high velocity is thin compared with the wave length, the laws of geometric seismics are not observed; a portion of the energy of the oscillations passes through this layer, without obeying the laws of geometric seismics, and waves are formed which glide over the deeper separation boundary with a lesser velocity. The waves corresponding to this boundary may be registered in the region of successive arrivals. In these cases the use of the CMRW makes it possible to study the behavior of the layers, which are characterized by a smaller velocity than certain of the rocks which are located above it [10].

Fig. 61a shows a seismogram, on which is registered the wave t_1 corresponding to a layer of limestones, located at a depth of approximately eight meters and having a velocity of approximately 4km/sec, as well as the waves t_2, t_3, and t_4, corresponding to deeper separation boundaries in a snadstone layer with velocities ranging from 2,000 to

2,800 meters per second. Fig. 115 shows the observed hodographs of the waves.

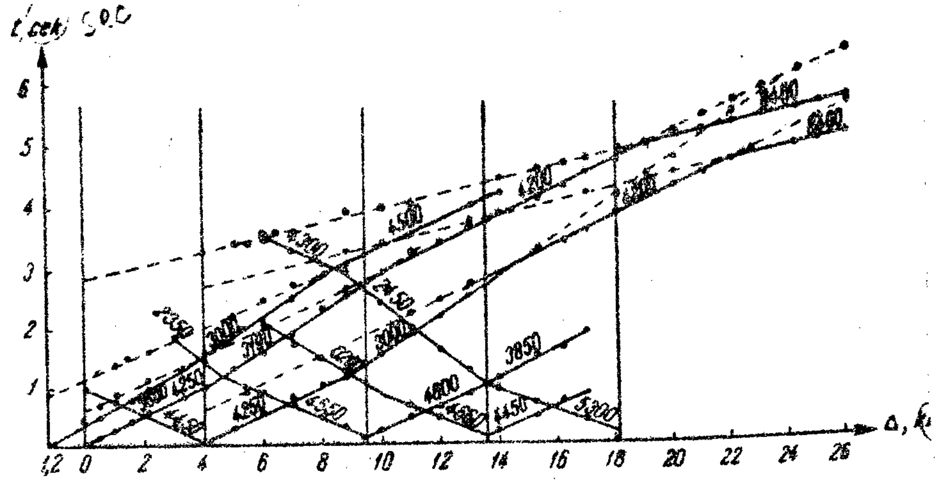

Fig. 117. Hodographs constructed by data obtained by the method of first arrivals (after Ye. A. Koridalin and S. I. Masarskiy [41]).

Study of the structure of media under conditions of sharp damping of the oscillations. The use of the method of first arrivals under conditions of sharp damping of the oscillations with increasing distance from the point of explosion cannot yield correct results owing to the small intensity of the individual waves or phases of one and the same wave, registered in the region of first arrivals at definite distances from the point of explosion. These oscillations may remain unobserved and then may assume for the first arrivals the more intense subsequent oscillations (see Chapters I and IV).

If one notes only the first arrivals, errors may result also from the fact that the transition from one wave to another or the transition from one phase of the same wave may remain unobserved. The consequence of errors of this kind may be incorrect conclusions regarding

the structure of the mdium. In particular, a smaller apparent velocity may be obtained, than the actual value and this will lead to a distortion in the form, depth, and velocity for the refracting boundary.

In the case of a sharp attenuation of the wave, erroneous conclusions may be drawn concerning the presence of steps, the presence of vertical separation boundaries, etc.

By way of an example one can show hodographs, constructed on the basis of data of the method of first arrivals for the Shatska rayon [41]. On the hodographs one notes (Fig. 117) branches with small apparent velocities, which the authors of the investigation have attributed to the presence of the layer with reduced velocity. An analysis of the shapes of the hodographs and the data given in reference [41] concerning the small intensity of the waves registered in this range of distances, lead to the conclusion that the presence of the branches of the hodograph with reduced velocity was in all probability due to erroneous separation of the arrivals in a zone of sharp attenuation of the waves.

The use of the correlation principle in tracing the waves makes it possible to investigate accurately the behavior of each of these waves and their mutual relationship with each other, and to clarify the true structure of the medium on the basis of these data.

Fig. 118 shows schematic seismic recordings and hodographs constructed in the correlation tracing of phases and by means of visible first arrivals. It is seen from the diagram that the hodograph based on the first arrivals noted on the recording differs sharply from the actual hodograph in the region where the wave t_1 is attenuated.

Study of the structure of the medium under conditions of gradual increase of the boundary velocity on going from the shallower to the deeper separation boundaries. If the boundary velocities increase relatively little when going from the shallower to the deeper refracting boundaries, and if the placement of the layers is

approximately conformed, the study of the structure of a stratified medium by means of the shape of the hodograph of the first arrivals becomes practically impossible. In this case the apparent velocity, determined by hodographs of the first arrivals, increases gradually with increasing distance from the point of explosion, and the hodographs of the first arrivals can be taken to be curved (Fig. 119b), which serves as grounds for obtaining a false idea concerning the types of the registered waves (lower part of Fig. 119b). As a result of this, false conclusions will be drawn concerning the velocity structure of the medium. A stratified medium will be assumed to be continuous, i. e., a medium in which the velocity increases monotonically with depth.

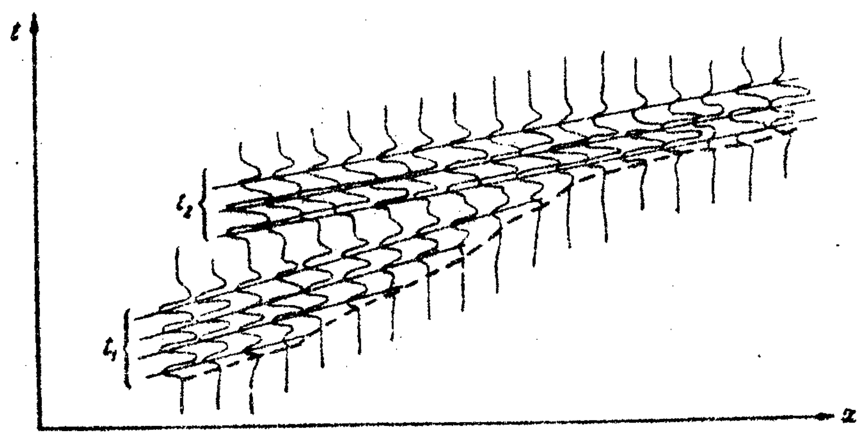

Fig. 118. Tracing of waves under conditions of sharp damping of the oscillations. The solid lines indicate the hodographs constructed with the correlation tracing of the waves; the dotted lines are hodographs constructed by visible first arrivals.

The tracing of waves in the region of succeeding arrivals - an analysis of the transition of the wave from the region of the first arrivals into the region of the succeeding arrivals - makes it possible to establish the

actual type of the waves, which are refracted (Fig. 119a), and to draw from the conclusion concerning the stratified structure of the medium (lower part of Fig. 119a).

By way of an example we can cite a hodograph of refracted waves obtained by the CMRW (Fig. 114). The hodograph shows clearly the straight-line branches, which go over from the region of first arrivals into the region of succeeding arrivals. If one imagines that only a first-arrival hodograph is available, it can be readily approximated by a smooth curve, which would give grounds for assuming that the velocity increases gradually with depth. We note that such an assumption concerning the velocity section through a given region existed prior to the application of the CMRW.

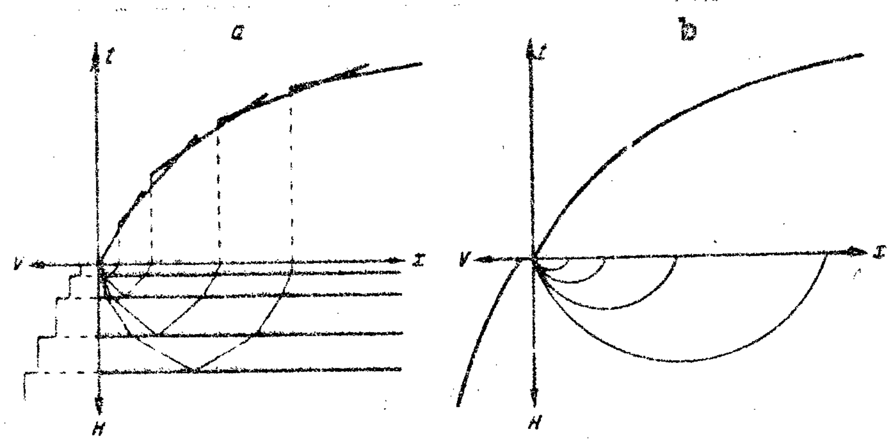

Fig. 119. Hodographs and corresponding schemes for the construction of media. a - hodograph constructed in the correlation tracing of waves (stratified medium); b - hodograph constructed from data of the method of first arrivals (continuous medium).

The comparison of the CMRW with the method of first

arrivals shows that the method of first arrivals has no advantage, but to the contrary, has many shortcomings compared with the CMRW. The use of the method of first arrivals cannot insure reliable results when solving the majority of problems possible in practice. The tracing of first arrivals is realized reliably with the aid of the CMRW.

Thus, the presence of the CMRW excludes the need of using the method of first arrivals. All the actually imaginable problems for the method of first arrivals must be solved with the aid of CMRW, not with the method of first arrivals.

2. Comparison of the CMRW with the Method of Reflected Waves

The correlation method of refracted waves and the method of reflected waves are based on the registration of waves of different types - refracted and reflected waves.

Frequency range. In the CMRW and in the method of reflected waves one uses in the most cases one and the same type of apparatus, tuned for the registration of approximately equal frequencies, ranging from 30 to 80 cycles. In some cases when working with the CMRW it is advantageous to go over to registration at lower frequencies.

Operating procedure. The procedure of observations in the method of reflected waves is simpler than in the CMRW. In addition, the procedure of observation with reflected waves is more standardized than the procedure of observation with refracted waves. The observation systems used in the CMRW depend substantially on the depth of the investigated separation boundaries and on the values of the velocities in the medium, whereas in the method of refracted waves the systems of observations in different regions and in the solution of different problems are for the most cases approximately the same. The simplicity and the standardization of the observation procedure in the method of reflected waves are the advantages of this method.

<u>Conditions of excitation of oscillations</u>. The CMRW is characterized by a considerably smaller dependence of the quality of the seismograms under conditions of excitation of oscillations, than for the method of reflected waves.

In many regions it becomes possible to register clear reflected waves only in the case of explosions in clay rocks and sufficiently deep holes (h = 30-50 meters). In the case of shallow holes and in the case when the explosions are made in sandy or cracked rocks, one frequently cannot record clear reflected waves.

It is possible to obtain recordings of refracted waves, as a rule, with explosions in sufficiently shallow bore holes. In some cases the use of the CMRW is possible also in the case of explosions in wells. Fig. 120 shows a seismogram, obtained with explosions in a bore hole of a depth of 6 meters at a distance r = 3115-3665 meters from the point of explosion.

<u>Number of traceable waves</u>. In most cases when working by the method of reflected waves one can register more waves than in observations by the method of refracted waves.

<u>Regions of traceability of the waves</u>. Depending on the regions of traceability of the reflected and refracted waves and on the conditions of registration of these waves, either method may be better. In some regions the reflected waves can be traced continuously only at relatively short sections. Under the same conditions the regions of traceability of the refracted waves are considerably greater.

An example of this is the data obtained in eastern Apsheron and in the Tuymazinskaya rayon, where a continuous tracing of the reflected waves in many cases is possible only over relatively short sections of the profile and not everywhere; on the other hand refracted waves were traced continuously over a long distance. The possibility of continuous correlation of waves at longer intervals makes it possible to give preference to the CMPW over the method of reflected waves. This is particularly important in those cases, when the layers are not coordinated and

when the problem of the investigations consists of studying the behavior of the definite separation boundaries, located in this section, i. e., when the construction of the arbitrary levels cannot insure sufficient accuracy.

In the case of weak velocity differentiation of rocks by velocities, the reflected waves that correspond to sufficiently remote separation boundaries may be traced separately in the region close to the point of explosion. Under the same conditions the refracted waves that correspond to the same two boundaries may form one complex interference oscillation over the entire extent of the profile. In this case the method of reflected waves has advantages over the CMRW. In the case of considerable differentiation of the boundary velocities, for two closely located separation boundaries, the reflected waves can be traced only under conditions of interference phenomena, and the refracted waves can be resolved on the recordings upon choice of suitable procedure of observations. In this case the advantages are in favor of the CMRW.

Determination of the velocity section. In the interpretation of the hodographs of reflected and refracted waves it is possible to determine different parameters, which characterize the velocity structure of the investigated medium.

From the hodographs of the reflected waves it is possible to determine the average velocity. In the presence of a series of hodographs of reflected waves, corresponding to the separation boundaries located at different depths, one can calculate from the values of the average velocities the layer velocity in the intervals between the reflecting boundaries. We note that the value of the layer velocity is determined with little reliability by means of data of the method of reflected waves [33].

From the hodographs of the refracted waves one determines the boundary velocities in the refracting layers. The value of the boundary velocities determines very reliably under considerable variations of the value of the velocity of the covering medium [33].

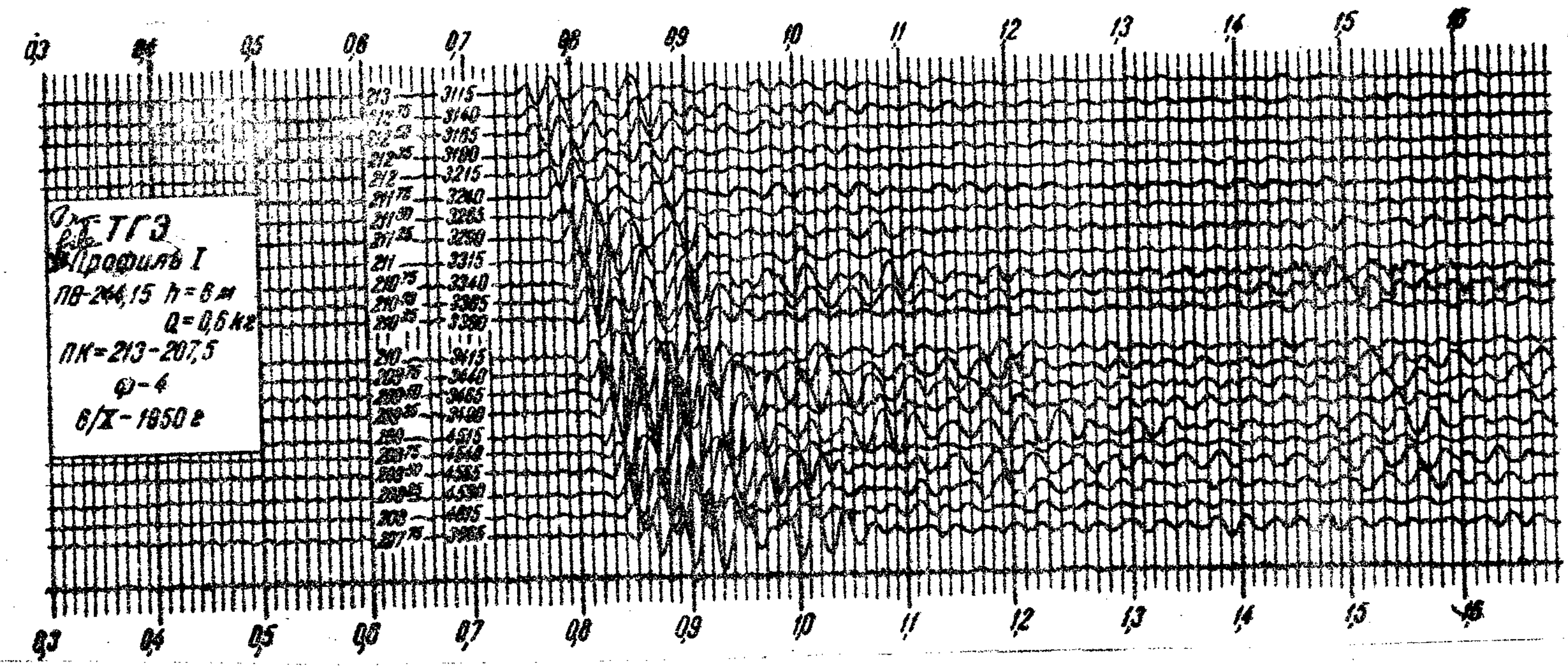

Fig. 120. Seismogram obtained in the case of an explosion in a shallow well: h = 6 meters, Q = 0.6 kg, r = 3115-3665 m.

The experimental data show that the values of the boundary velocities as a rule cannot be extended over the entire layer contained between the refracting boundaries. The boundary velocities V_b correspond for the most part to the more or less thin layers with greater velocities between the surrounding rocks. The values of the boundary velocities characterize the physical properties of the refracting layers. Knowledge of this quantity facilitates the correlation of the separation boundaries, the comparison of the seismic sections with each other in the case when the measured sections are separated or when the breaks are absent in the correlations; in addition, they make it possible to carry out more reliably the identification of the seismic boundaries with the geological ones.

In some cases one can determine from the CMRW data the average velocity $\bar{V}$ (based on the initial points, or points in the breaks in the hodographs). Experiments have shown that data on V, obtained by the method of refracted waves, are usually insufficient to judge the character of variation of the average velocity with depth or along the profile, and are more so insufficient for the determination of the layer velocities.

Depth of investigation. For the method of reflected waves, the investigation of separation boundaries located at small depths (up to 300-400 meters) is rarely possible; an investigation of great depths (4,000-5,000 meters), the method of reflections does not yield in some cases reliable materials, owing to the absence of clear reflections, owing to the presence of multiple waves, etc. The CMRW makes it possible to investigate both small and large depths. In the investigation of large depths, when it is necessary to carry out observations at great distances from the point of explosion, good conditions are necessary for the CMRW with respect to excitation of the oscillations (water reservoir, deep shot holes).

Role of noise. In regions where intense noise is produced by waves propagating in the surface layers (surface waves, reverberation in the sea), the use of the method of reflected waves becomes difficult or impossible because of the fact that the noise arrives simultaneously with the reflected waves or masks them (Fig. 121).

For the method of refracted waves these noises do not play a substantial role, since the regions of registration of noise in the refracted waves, as a rule, are different (Fig. 121).

An example are the zones of "reverberation" in the sea, in the region of the Apsheron peninsula. Reverberation oscillations are registered in the same time range as the reflected waves, and interfere with the separation of the latter. For the refracted waves, the presence of reverberation noise is important, since the refracted waves are registered at small times, and the reverberation oscillations do not interfere with their separation.

Study of thin layers. Thin layers, characterized by velocities greater than the velocities in the surrounding rocks, can be investigated to advantage with the aid of the CMRW.

As indicated in Chapter I, the refracted waves are formed at very small ratios $\frac{d}{\lambda}$ (thickness of the layer to the wavelength). These waves have, at certain distances fro the point of explosion, a considerable intensity and are clearly separated on the recordings. The separation of waves reflected from thin layers is not always possible. The phenomenon of reflections from thin layers has been investigated theoretically and experimentally for other branches of physics (acoustics, optics). The data obtained indicate that in the case of thin layers the greater pert of the energy of the wave passes through the thin layer and only a very small fraction of the energy is reflected. An analogous phenomenon can serve as the cause of absence of very low intensity of seismic waves reflected from a thin layer.

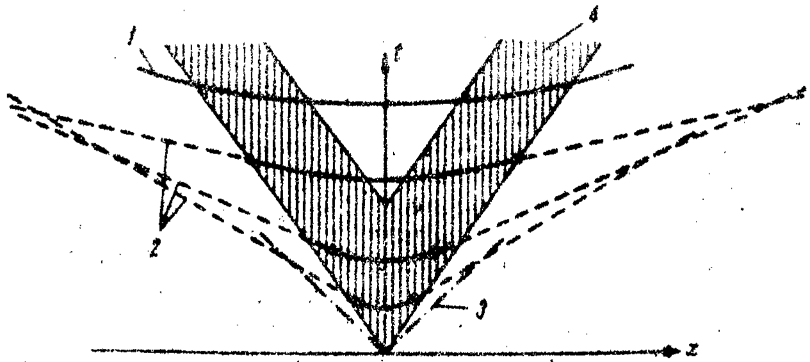

Fig. 121. Arrangement of the regions of tracing of different waves: 1 - reflected (solid line); 2 - refracted (dotted); 3 - direct (dash-dot), and 4 - surface (shaded).

<u>Study of poorly reflecting separation boundaries</u>. It is known that certain clear refracting boundaries, such as the surface of salt domes and the surface of a crystalline foundation, are frequently poor reflectors. This may be due to the fact that the boundaries have a "rough" or "wavy" form. Such boundaries scatter for the most part the incident seismic waves; no regular reflections are formed at the relatively high frequencies used in the method of reflections [48]. For refracted waves, immerging from the lower medium, experiment has shown that the scattering properties of such a boundary are not as important.

The second cause of the absence of reflections from certain separation boundaries may be the presence of a transition zone at the boundary, i. e., a zone in which the acoustic stiffness changes smoothly with depth [48]. The presence of such a zone for the formation of refracted waves, as indicated by experimental data, may be insignificant.

It is known that the surface of crystalline rocks has an uneven form and is frequently characterized by the presence of a "weathering" zone, in which the velocity and density increase with depth. The surface of salt domes also frequently has an uneven rough form. Such singularities may

be had also by other separation boundaries, and this should cause difficulties in the registration of the reflected waves.

Solution of structural problems. In the disclosure and investigation of structural forms under conditions when the layers at considerable epth intervals are coordinated, both the method of reflected and refracted waves can be used. The advantages of one or the other methods are determined by the ratios of the velocities, by the thickness of the layers, by the depth of the investigation, etc.

To investigate the structural forms in an uncoordinate location of the layers, under a favorable velocity ratio (see Chapter VII), the CMRW has many advantages over the method of reflected waves. The basis for this is the possibility of determining the boundary velocity and the possibility of continuous tracing the wave over large distances.

An investigation of faults is possible primarily with the aid of the CMRW. Here it is possible to trace the refracting boundaries and to determine the amplitude of the fault by comparing the values of the boundary velocities, obtained on both sides of the fault line. The same conclusion can be made also for tapering layers.

An investigation of a medium with vertical or steeply-inclined boundaries is possible with the aid of the CMRW. A detailed analysis of the form of the recordings, the identification of special types of waves occuring with such a structure of the medium, and an analysis of the data regarding the boundary velocities make it possible to investigate the structure of media of this kind (see Chapter VII).

The comparison shows that the prospecting capabilities of the CMRW and of the method of reflected waves partially coincide, and partially differ from each other. One method cannot replace the other completely.

In solving certain problems it is advantageous to use the CMRW, and in solving others - the method of reflected waves, and in solving a large number of a third kind of

problems it is advisable to use both methods simultaneously. This question is discussed in the next chapter.

Chapter IX

COMBINATION OF THE CMRW AND THE METHOD OF REFLECTED WAVES

1. Grounds for Combined Application of the Two Methods

A comparison of the correlation method of refracted waves and the method of reflected waves, as well as an analysis of the experimental material obtained with each of these methods in the same regions, is evidence that it is possible in principle and advantageous in practice to employ simultaneously both methods at all stages of work, from the process of obtaining the seismogram to the final interpretation of the material.

The method based on the simultaneous use of the method of reflected waves and the CMRW was called the combined method of seismic prospecting [26].

Existence of reflected and refracted waves. Many experiments in various regions have shown the existtnce of reflected and refracted waves, corresponding to separation boundaries contained in the section of each given region. Judging from the seismic data, some separation boundaries are reflecting and others refracting, while still others are both reflecting and refracting. The presence of reflecting and refracting separation boundaries in one and the same geological section is the physical ground reason for employing the combined method.

Methods of separating and tracing waves. The separation and the tracing of reflecting and refracting waves is based on the general principles of phase correlation.

The frequency spectra of the reflected and refracted waves are in many cases similar to each other. This causes the apparatus used in the registration of reflected and refracted waves to be quite similar. The fact that the same type of apparatus is used makes in turn the seismic recordings common, and this makes it possible to carry out the separation and tracing of reflected and refracted waves on one and the same set of seismograms. Fig. 61a shows the seismograms, on which are registered the refracted waves t_1, t_2, t_3, and t_4 and the reflected wave t_5, corresponding to different separation boundaries.

Prospecting capabilities of the methods. The prospecting capabilities of the methods of reflected and refracted waves, as follows from the preceding chapter, frequently coincide, and are frequently different. This makes it possible, in combined application of the two methods, to compare and interrelate the data of these methods and, what is most important, to obtain more complete and exact information on the structure of the investigated medium, than if only one of the methods is used. The latter reduces essentially to the following:

1. The construction of sections by hodographs of refracted waves can be carried out more accurately in the presence of data on the average velocities, determined by the hodographs of the reflected waves.

2. Sections constructed by hodographs of reflected waves can be supplemented with data on the boundary velocities, determined by the hodographs of the refracted waves. This makes it possible to obtain the physical characteristics of the reflecting boundaries, to facilitate the compilation of the seismic data with the geological one, and to interrelate the seismic data, obtained at unrelated observation regions.

3. A more complete and more exact study of the velocity section is possible. Information on the average layer velocities (method of reflected waves) and boundary velocities (CMRW) make it possible to compile a most complete representation of the physical characteristics of the medium. Particularly important are data on the boundary velocities, equal to the true velocity of propaga-

tion of the waves along the refracting layer.

Comparison of the data concerning the medium, layer, and boundary velocities make it possible to refine the velocity section: to exhibit the presence of thin layers with increased velocities, to determine the velocities in them, and to estimate the maximum thickness; to estimate the value of the layer velocities in layers whose boundaries are determined by data of the method of refracted waves, etc.

2. Mixed Correlation of Reflected and Refracted Waves

As noted in Chapter IV, the regions of registration of reflected and refracted waves are different. Reflected waves usually can be traced over an interval from the point of explosion to the initial points of the hodographsof the refracted waves; at distances greater than the distance to the initial point, these waves cannot be separated on recordings, in all probability because of their small intensity compared with the refracted waves and owing to the possible disturbances in the phase correlation. The refracted waves can be registered starting with the initial point, towards the side of larger distances.

The correlation of reflected and refracted waves in the regions of their separate existence is carried out by well known methods (see Chapter IV). The singularity of the correlation of the waves when working by the combined method consists principally of correlation of the oscillations near the initial point. This question is discussed partially in Chapter IV.

Depending on the features of the correlation in the region of the initial point, one can distinguish the following cases:

a) The reflected waves are traced at distances $0 < x < x_{ip}$, while the refracted waves at distances $x > x_{ip}$. The initial points are noted by means of clear

cut dynamic symptoms. At the initial point there is a discontinuity in the correlation of the waves. During the time of the registration, it is possible to assign the reflected and refracted waves to one and the same separation boundary judging from the shape and position of the hodographs, and from the quality of the values of V* at the initial point.

It is thus possible to delineate in this case the regions of registration of the reflected and the refracted waves and to interrelate the waves corresponding to one and the same separation boundary.

b) in the region of the initial point, the correlation is continuous, the reflected wave is replaced by a refracted one wothout a noticeable change in the character of the record; the initial point is not segregated with the aid of the shape of the record. It is usually difficult to establish the position of this point from the shape of the hodograph, since the hodograph of the reflected waves near the initial point is close in form to a straight line and clear changes in the form of the hodograph are not noted. In this case the reflected and refracted waves corresponding to one and the same separation boundary are accurately interrelated, but the delineation of the regions of registration of these waves cannot be carried out with the sufficient accuracy.

c) The intensity of the reflceted waves changes sharply with distance and it is impossible to separate the reflected waves near the initial point. The initial point is clearly noted from the occurrence of refracted waves. In this case it is impossible to recognize the types of waves, but an exact interrelation of the waves, corresponding to one and the same separation boundary, is impossible.

All the foregoing cases were noted in experimental investigations. Theoretically one can imagine still another case, when the reflected waves are traced at distances $x > x_{ip}$.

d) In the region of the initial point one notices the interference of reflected and refracted waves, corres-

ponding to one and the same separation boundary. Depending on the character of the interferences, cases may occur when the data obtained make it possible to establish whether the reflected or refracted waves belong to one and the same separation boundary and the position of the initial points will be determined. In other cases the clarification of one or two of these questions will be impossible.

3. Combined Hodographs

When working with the combination method, the hodographs are obatined of the reflected waves and of the refracted waves. Let us consider the hodographs of the waves corresponding to one and the same separation boundary. We shall call a hodograph combined, if it is obtained for the same point of explosion, and consists of the hodograph of the reflected waves and one or two hodographs of the refracted waves, corresponding to the same separation boundary (Fig. 122). We shall call a system of hodographs the correlated hodographs corresponding to the same separation boundary. Systems of hodographs consisting of combined hodographs will be called combined systems. Systems of hodographs consisting of all the hodographs of reflected waves or only of hodographs of refracted waves will be called homogeneous systems.

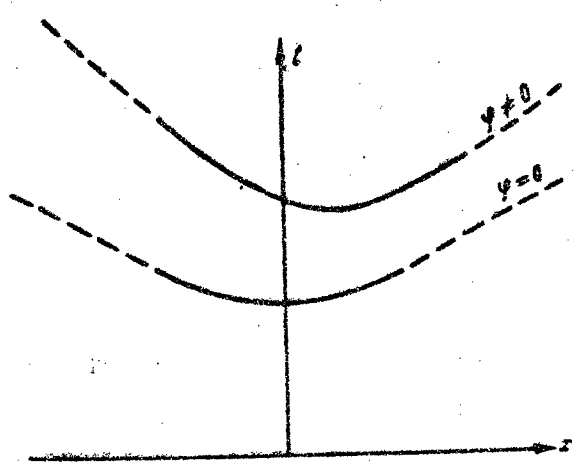

Fig. 122. Combined hodographs in the cases $\varphi = 0$ and $\varphi \neq 0$

The hodograph of refracted waves is tangent to the hodograph of reflected waves at the initial point. In the case of a plane separation boundary the hodograph of reflected waves is a hyperbola, while the hodographs of the refracted waves are straight lines. In the region close to the initial point, the difference in the shape of the hodographs is small, since at large distances from the point of explosion the hodographs of the reflected waves are nearly a straight line. The apparent velocity is determined by the hodograph of the refracted waves, and by the hodograph of the reflected waves are the same in the section that includes the initial point.

<u>Systems of combined hodographs</u>. Systems of combined hodographs can be quite varied. We shall describe only several systems, corresponding to a medium with one separation boundary of arbitrary shape, and we shall list the quantities that can be determined by means of these systems.

1. The simplest system a consists of one combined hodograph (Fig. 123a). Hodographs of this type can be used to interrelate hodographs of refracted waves, obtained on different sides of the point of explosion. In addition, such a system will make it possible to determine the velocity and to construct the separation boundaries. The system is sufficient for a unique interpretation under the condition $\bar{V}$ = const and V = const, and also in the case when the shape of the separation boundary does not differ greatly from plane in the section corresponding to the hodograph of reflected waves. On the section to which the hodographs of refracted waves correspond, the shape of the separation boundary may also be arbitrary.

From the section of the hodograph which is known to belong to the reflected-wave hodograph, it is possible to determine the average velocity $\bar{V}$ and to construct the section of the separation boundary. If the position of the initial point is known, it is possible, knowing the value of the average velocity $\bar{V}$, to determine from the coordinates of these points the boundary velocity V_b. From the hodographs of the refracted waves it is possible to construct the refracting boundary.

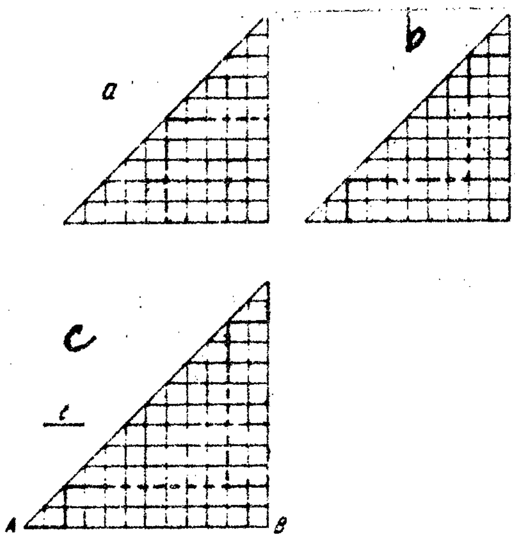

Fig. 123. a, b, c, — systems of combined hodographs; —— -- reflected waves; ---- -- refracted waves

The system b consists of two opposite hodographs of refracted waves, each of which is connected with the hodograph of reflected waves. The system is interrelated by mutual points of the hodographs of the refracted waves (Fig. 123b).

At an unknown velocity in the covering medium, the system b is sufficient for unique interpretation provided $\bar{V}$ = const and provided the shape of the separation boundary is close to the plane in the sections that correspond to the hodographs of the reflected waves. The following can be determined here: $\bar{V}$ (from the hodographs of the reflected waves), V_b (from the opposing hodographs of the refracted waves), and the position of the separation boundary (from the hodographs of both types of waves).

The system b is sufficient for unique interpretation, provided the velocity in the covering medium is

variable and is a specified function of the coordinates $\overline{V} = V(H, x)$. If we do not have a specified $\overline{V} = \overline{V}(H, x)$, but it is known that the angles of the inclination of the separation boundary are small and the changes of $\overline{V}$ with depth and with distance are small, then it is possible to determine approximately, from the hodographs of the reflected waves, the values of $\overline{V}$ and these values can be used to construct the separation boundary over the entire system of combined hodographs. The determination of V_b in this case is sufficiently accurate.

The system b can be used for identification of reflected waves, corresponding to one and the same separation boundary, and for interrelation of data obtained with the aid of the method of reflected waves on separated sections.

3. The system c consists of the system b, to which are added opposite hodographs of reflected waves, interrelated by mutual points with the hodographs of the reflected waves of the system B (Fig. 123c). If the velocity in the covering medium is unknown, the system is sufficient for unique interpretation at $\overline{V}$ = const and for an arbitrary shape of the separation boundary. The following can be determined: $\overline{V}$ (from hodographs of refracted waves), and the position of the separate boundary (from the entire hodograph).

Unlike the system b, the system c insures the possibility of determining $\overline{V}$ from the hodographs of reflected waves in the case when the separation boundary has a curved form (by mutual points of the hodographs of reflected waves and by opposite hodographs). In the case when $\overline{V}$ is a specified function of the depth, $\overline{V} = V(H)$, the system c is sufficient for a unique determination of V_b and of the position of the separation boundary which may have an arbitrary form. If there is no specified $\overline{V} = V(H)$, then the system c, like the system b, is sufficient for an approximate interpretation.

<u>Comparison of the combined and homogeneous systems</u>. For the purpose of comparison of combined systems with homogeneous systems, let us consider as an example the homogeneous system that can replace the combined system a.

The system a makes it possible to correlate two hodographs of refracted waves, obtained with explosions at a single point. To solve the same problem by the method of refracted waves one would find it necessary to obtain two hodographs of refracted waves from two additional explosion points (Fig. 124a).

By way of a second example, let us compare the homogeneous systems with the combined system c. We assume that l is the usually employed interval of tracing of reflections on one side of the explosion point; the length of the profile is 6 ℓ; we shall assume that the waves refracted from the separation boundary are easiest to trace in the interval from 1.5 to 4 ℓ from the point of explosion.

Under these conditions, for a continuous correlation of the reflected waves along a profile of length 6 l, it is necessary to have seven explosion points(Fig. 124b). For a continuous correlation of the refracted waves - five explosion points are necessary (Fig. 124c). Thus the number of explosion points necessary in observations by the method of reflected waves or by the method of refracted waves (7 or 5) is considerably greater than the number of explosion points of the system b of Fig. 123, necessary in the investigation of the same separation boundary with the aid of the combined method. The volume of observations in this case is also considerably less, as can be seen clearly from a comparison of Fig. 123a with Figs. 124b and c.

In the interpretation of a combined system one can obtain more complete data than in the interpretation of a homogeneous system. In the interpretation of a system that consists only of hodographs of reflected waves (Fig. 124b) one can determine the following average velocity along the entire profile and the position of the separation boundary. In the interpretation of a system consisting of hodographs of refracted waves (Fig. 124c), the following can be determined: Boundary velocity and the position of the separation boundary. In the interpretation of a combined system the following can be determined: $\overline{V}$, V_b, and the position of the separation boundary.

Summarizing, one can note that combined systems

cannot be replaced in the majority of cases by homogeneous systems as regards the completeness of the results obtained in their interpretation. Continuous correlation in the production of combined systems can in many cases be realized at a smaller number of observations, than if homogeneous systems are obtained under the same conditions.

<u>Ratio of the number of observations of reflected and refracted waves needed in the case of combined systems.</u> Depending on the data and form of measurements, the hodographs of the refracted waves may become more or less significant in the combined systems. For example, when solving various types of stratigraphic problems, when it is necessary to separate and trace the definite separation boundaries, the number of observations by means of each of these methods can be approximately the same or else the dominating role may belong to the method of refracted waves. From the value of the boundary velocity one can identify here the portion of the separation boundary, which is separated as a result of damage, and the amplitudes of these damages can be determined.

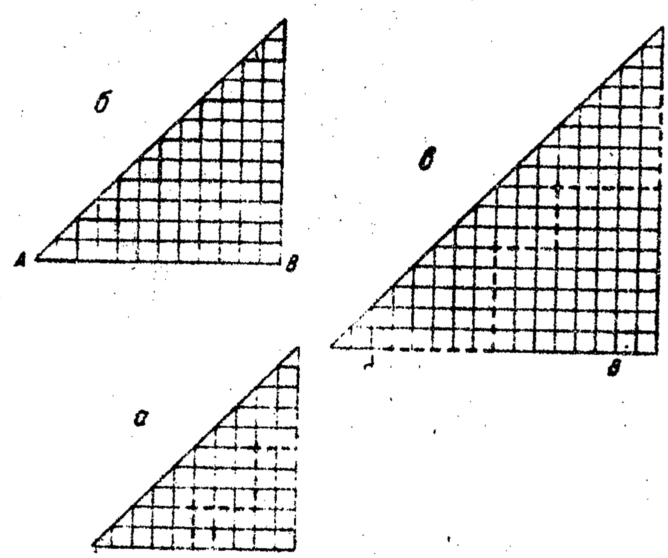

Fig. 124 a, b, c, -- systems of homogeneous hodographs, ——— -- reflected waves, ---- -- refracted waves.

In the investigation of regions that are characterized by the presence of small structures, or if it is necessary to investigate a large number of separation boundaries, the principal role in the combined method may belong to the method of reflected waves. In reconnaissance measurements, when it is necessary to obtain a general idea of the behavior of the separation boundary with a minimum volume of of observations, observations at individual isolated profiles by the method of the combined systems of various types may be preferable. The values of the boundary velocities facilitate the interrelation of the data obtained on separated sections. The number of observations in each of these methods can be the same in these cases.

Example. By way of an example of a combined system of observations in the investigation of several separation boundaries, we give a scheme of observations that can be employed under conditions analogous to conditions of eastern Apsheron, where separation boundaries located at great depth (up to 3.5 or 4 kilometers) must be investigated. The initial data for the combination of the scheme are the following: a) there are two reference levels (boundaries A and B) in the prospected interval of depths; b) the investigation of boundary A, located at a depth of 1-1.5 kilometers, can be most simply carried out by obtaining a system of hodographs of refracted waves; the optimum interval of tracing these waves is 3-10 kilometers from the point of explosion. The method of reflected waves is applicable for the investigation of the boundary A owing to the presence of interference from surface waves; c) the investigation of the boundary B, which is located at a depth on the order of 3 or 4 kilometers, can be carried out most reliably by means of obtaining combined systems of hodographs; the optimum intervals of tracing the reflected waves are 2-5 kilometers, and that of refracted waves is 5-10 kilometers from the point of explosion.

On Fig. 125 is shown a combination scheme using a longitudinal profile for the investigation of the foregoing two separation boundaries. The system given makes it possible to study the boundaries A and B for the same points of explosion.

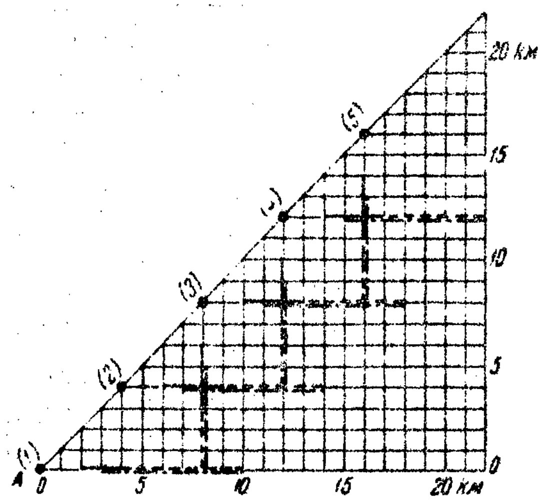

Fig. 125. Example of combined system: ——— -- reflected waves, ---- -- refracted waves (boundary A); -•-•-• -- refracted waves (boundary B).

4. Increase in the Accuracy of the Interpretation Results

We shall show that in the presence of combined data it is possible to obtain more accurate values of the depths and angles of inclination of a separation boundary, consequently to obtain a more accurate velocity cross section in the covering medium.

The accuracy of interpretation of seismic data is determined in most cases by the accuracy with which the value of the velocity in the covering medium is given and by the correctness of the method chosen for the replacement (approximation) of the real covering medium by a certain fictitious medium. In an interpretation, the real multiply-layered or continuously-stratified medium is replaced by a homogeneous medium (the method of average velocities), and in certain cases by a medium consisting of a small number of layers with constant velocities, or else by a continuous medium, the velocity in which increases

with depth linearly. If inexact values are assumed in the interpretation for the velocities or if the method of approximation is incorrectly chosen, then in the calculation this leads to errors in d pth and shape of the investigated separation boundaries. The values of the errors in the angles of inclination and depths of the separation boundaries are different when they are determined by hodographs of reflected and refracted waves [31a]. The difference in the values of the angles of inclination and depths of the separation boundaries, determined by hodographs of reflected and refracted waves, corresponding to one and the same boundary, may serve as an indication of the error in assuming the velocity cross section of the covering medium as assumed for the interpretation. Only in the absence of such errors do the sections, constructed by hodographs of reflected and refracted waves, coincide with each other and with the true position of the separation boundary.

Thus, the agreement between the separation boundaries constructed by hodographs of reflected and refracted waves, which are correlated with each other, can serve as a criterion of the correctness of the interpretation. Lack of agreement between these sections indicates the interpretation is in error. By successive variations in the values of the velocities in the covering medium it is possible to attain agreement between separation boundaries and to determine the true value of the velocity in the covering medium.

We shall show that the difference in the angles of inclination and depths, in the case of inaccurate data on the velocity section of the covering medium, may be quite considerable in practice, and consequently it can be used for interpretation. Let us consider the question of the error in the determination of the angles of inclination and depths of the separation boundary for the simplest case of a plane separation boundary (angle φ) and constant values of velocities in the covering medium V_1, and in the refracting medium V_2. We shall assume that the velocity V_1 is specified with a relative $m = \Delta V_1/V_1$.

1. Determination of the Angles of Inclination

Hodograph of refracted waves. The error $\Delta\varphi$ in the angle of inclination, determined by means of a linear hodograph of refracted waves with apparent velocity V*, is given by the following formula

$$\Delta\varphi = \pm\left[\arcsin\frac{V_1}{V_2}(1+m) - \arcsin b(1+m)\right] - \varphi, \qquad (56)$$

where $b = V_1/V^*$.

In the interpretation by means of two opposing hodographs, the formula for $\Delta\varphi$ has the following form

$$\Delta\varphi = \frac{1}{2}\left[\arcsin\frac{V_1}{V_-^*}(1+m) - \arcsin\frac{V_1}{V_+^*}(1+m)\right] - \varphi, \qquad (57)$$

where V^*_- and V^* are the apparent velocities, determined by the two opposing hodographs of refracted waves.

An analysis of the formulas (56) and (57) shows that the absolute value of the error in the angle of inclination, due to inaccurate knowledge of the velocity in the covering medium, increases with the value of m, with the value of φ, and with the ratio V_1/V_2. The sign of $\Delta\varphi$ coincides with the sign of φ when $m > 0$; when $m < 0$, the sign of $\Delta\varphi$ is opposite to the sign of φ.

Hodograph of reflected waves. In the determination of φ from an element of hodograph of reflected waves, characterized by a time of arrival t and by an apparent velocity V*, the error $\Delta\varphi$ in the angle of inclination is given by the following formula

$$\Delta\varphi = \operatorname{arc\,tg} \frac{\operatorname{tg}\varphi\sqrt{1-b^2} - bm(2+m)}{(1+m)\sqrt{1+b^2(1+m)^2}} - \varphi \qquad (58)$$

Replacing b by the ratio $(x-x_m)/2H$, where x_m is the abscissa of the minimum point of the hodograph, we obtain

$$\Delta\varphi = \operatorname{arc\,tg} \frac{\sin\varphi - m\dfrac{x-x_m}{2H}(2+m)}{(1+m)\sqrt{\cos^2\varphi - m(2+m)\left(\dfrac{x-x_m}{2H}\right)^2}} - \varphi \qquad (59)$$

The magnitude and the sign of the error $\Delta\varphi$ in the angle of inclination depend substantially on the position of the interpreted portion of the hodograph. The most accurate determination is by means of the hodograph element located in the region between the minimum of the hodograph and the point of explosion. The farther the hodograph element from this section, the lesser the accuracy with which the angle of inclination is determined. When $\overline{V}'_1 \neq \overline{V}_1$; the interpretation of the entire hodograph of reflceted waves leads to a distortion in the shpae of the separation boundary.

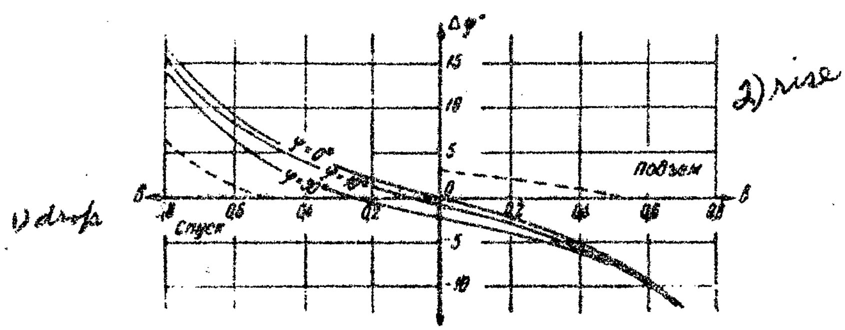

Fig. 126. Graphs showing the dependence of $\Delta\varphi$ on $b = V_1/V^*$; $m = 0.1$, $V_1/V_2 = 0.5$. ——— -- reflected waves, ---- -- refracted waves. 1) drop, 2) rise

Combined data. We denote by $\Delta \varphi_{refl}$ the magnitude of the error in the angle of inclination as determined by a reflected-wave hodograph element at the initial point of hodograph of refracted waves, and by $\Delta \varphi_{refr}$ the value of the error in the angle of inclination when determined by a single refracted-wave hodograph. Let us compare $\Delta \varphi_{refl}$ with $\Delta \varphi_{refr}$, due to erroneous values of the velocity in the covering medium under all these conditions, which were assumed in the examination of the corresponding questions for hodographs of reflected waves and forhodographs of refracted waves.

A comparison of formulas (58) and (56) shows that $\Delta \varphi_{refl}$ and $\Delta \varphi_{refr}$, for the same values of b (which is characteristic of the considered element of the hodograph of reflected waves and hodographs of refracted waves), are in general different.

Fig. 126 shows graphs of the dependence of $\Delta \varphi$ on b for reflected and refracted waves, calculated by means of formulas (58) and (56). In the calculations it was assumed that m = 0.1 and $V_1/V_2 = 0.5$. For reflected waves, curves are given for $\varphi = 0^o$, $\varphi = 10^o$, and $\varphi = 30^o$. For certain values of angle of inclination φ at m = 0.1 and $V_1/V_2 = 0.5$, the values of $\Delta \varphi$ are listed in Table 10.

Table 10

φ	1) По подъему		2) По спуску	
	$\Delta\varphi_{отр}$ refl.	$\Delta\varphi_{пр}$ refr.	$\Delta\varphi_{отр}$ refl.	$\Delta\varphi_{пр}$ refr.
0	—6,5	0	6,5	0
10	—4,3	1,2	9,1	2
20	—2	2,3	13	4,4

1) by rise, 2) by drop

Comparison of the values of $\Delta\varphi_{refl}$ and $\Delta\varphi_{refr}$ shows that only when m = 0 do the angles of inclination of the separation boundary, determined by the element of hodograph of reflected waves and by the hodograph of refracted waves, have the same values and are equal to the true values. When $m \neq 0$ the values of $\Delta\varphi_{refl}$ and $\Delta\varphi_{refr}$ do not coincide in magnitude, and when $\varphi >$ they are of opposite sign. The difference in the values of $\Delta\varphi_{refl}$ and $\Delta\varphi_{refr}$ reaches large values.

Thus, the discrepancy in the angles of inclination and the shape of the separation boundaries, constructed by hodographs of reflected and refracted waves, forming the combined hodograph or obtained with the same sections, may serve as an indication of the erroneousness of the assumed value of the velovity in the covering medium. The equality of the angles of inclination $\varphi_{refl} = \varphi_{refr}$ is evidence of correctness of the assumed value of the average velocity.

2. Determination of the Separation-Boundary Depth

<u>Hodograph of refracted waves</u>. The relative error $\Delta h/h$ in depth along the normal to the separation boundary, determined by the hodographs of the refracted waves, in the case of a straight separation boundary and constant values of the velocity V_1 and V_2, depends on m, V_1, and V_2 in the following manner:

$$\frac{\Delta h}{h} = (1+m)\frac{\sqrt{1-\left(\frac{V_1}{V_2}\right)^2}}{\sqrt{1-\left(\frac{V_1}{V_2}\right)^2(1+m)^2}} - 1. \qquad (60)$$

As can be seen from formula (60), the value of $\Delta h/h$ increases with increasing m and with increasing V_1/V_2. The sign of $\Delta h/h$ is the same as the sign of m.

Fig. 127 shows graphs of the dependence of on m at different ratios V_1/V_2. The graphs show that the

absolute values of the errors in the depth are particularly large when m > 0.

Hodograph of reflected waves. In the interpretation of the hodograph of reflected waves, the error in depth along the normal dropped from the point of explosion to the separation boundary, is given by the formula

$$\frac{\Delta h}{h} = (1+m)\frac{\cos\varphi}{\cos(\varphi+\Delta\varphi)}\frac{\sqrt{1-b^2(1+m)^2}}{\sqrt{1-b^2}} - 1. \qquad (61)$$

and the particular case when $\varphi = 0$ and b = 0, formula (61) becomes

$$\frac{\Delta h}{h} = m. \qquad (62)$$

Since the quantity $\Delta\varphi$ is different for different portions of the hodograph, then in the interpretation of an extended hodograph of reflected waves the error in the determination of the depth will be different for different hodograph elements.

The solid lines of Fig. 128 show the calculated position of the reflecting boundary as obtained from a specified hyperbolic hodograph of reflected waves at different values of m (the diagram is taken from reference [53]). As can be seen from the diagram, an erroneous value of the velocity in the covering medium leads to an error in the depth and shape of the separation boundary.

Combined data. Comparison of formulas (60) and (61) shows that the magnitudes of the relative errors in the depth are different for the hodographs of the reflected and the refracted waves when m $\neq 0$. The greater the value of m, the greater the discrepancy in the depths. The differences in the depth and the form are particularly large when m > 0.

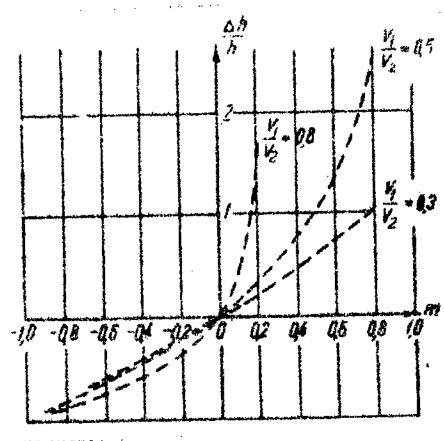

Fig. 127. Graphs showing the dependence of Δ h/h on m.

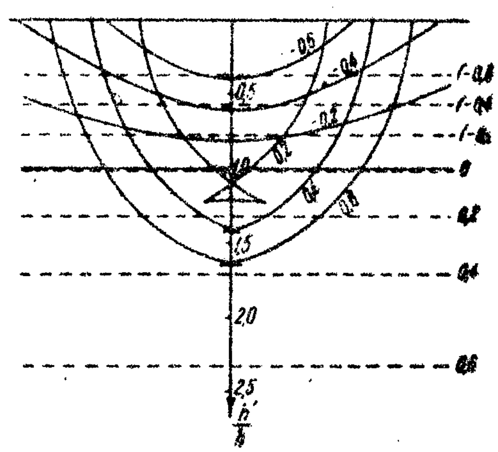

Fig. 128. Position of reflecting and refracting boundaries at different values of m = V_1/V_2. ——— -- reflected waves, ---- -- refracted waves.

Fig. 128 shows a comparison of the results of the determination of the position of the separation boundary by means of opposing hodographs of refracted waves and by means of a hodograph of reflected waves, corresponding to the same horizontal separation boundary at different values of V_1. As can be seen from Fig. 128, the "reflecting" and "refracting" boundaries coincide with each other only when $m = 0$, and here they coincide also with the true position of the separation boundary. For all other values of m the results of the determination of the position of the separation boundary by hodographs of reflected and refracted waves are different. The form of the separation boundary, constructed by hodographs of refracted waves, is linear, but that obtained by hodographs of reflected waves is curved; their depths are different.

By way of an example of the use of this criterion in the interpretation of observed data, we list the results of the construction of a section by means of a specified combined hodograph. Fig. 129 shows the following: a) combined hodograph, obtained at a point of explosion A consisting of a hodograph of reflected waves (solid line) and a hodograph of refracted waves (dotted), and b) hodograph of refracted waves (dotted), obtained at the point of explosion for 450 and interrelated by mutual points with the hodographs at the point of explosion O.

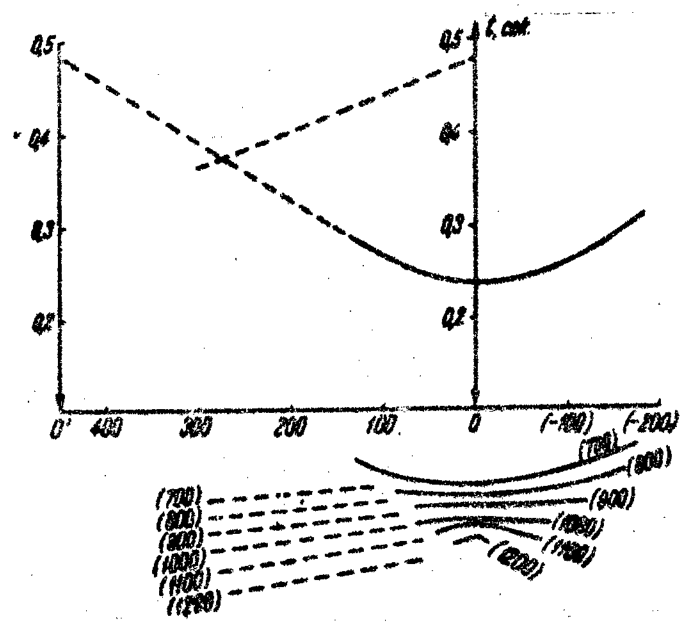

Fig. 129. Example of construction of a separation boundary by the combined hodograph.

The determination of the average velocity V by the hodograph of reflected waves, under the assumption that the separation boundary is plane, and that the covering medium is homogeneous, yields a value $\bar{V}$ = 850-900 m/sec. The separation boundary, constructed by the hodographs of reflected waves at $\bar{V}$ = 900 m/sec is shown by the solid line in the lower part of Fig. 129. The construction of the refracting boundary has been carried out by two opposing hodographs of refracted waves. The boundary constructed at $\bar{V}$ = 900 m/sec is shown by means of a dotted line. As can be seen from the diagram, the reflecting and refracting boundaries near these points of contact do not coincide in depth and differ in angle of inclination. This indicates that the value of $\bar{V}$ taken for the construction is in error. The construction of reflecting and refracting boundaries at values of $\bar{V}$ equal to 700, 800, 1,000, 1,100, and 1,200 m/sec (see Fig. 129) shows that only when $\bar{V}$ = 1,000 m/sec is the refracting boundary of a smooth continuation of the reflecting boundary. According to the results obtained above, this will be the true position of

the separation boundary, and the value $\bar{V}$ = 1,000 m/sec will be the true value of the average velocity in the covering medium. From these data it is seen that the construction of the section by the combined hodographs makes it possible to establish the true position of the separation boundary and simultaneously to refine the velocity section of the covering medium.

The conclusions obtained are valid also for more general cases of curved separation boundaries, for a more complex covering medium (stratified, continuous), and in the solution of not a two dimensional but a three dimentional problem.

The increase in the accuracy of the seismic prospecting when using the combined method has a great practical significance, particularly when solving structural problems that require the determination of the position of the separation boundary by small angles of inclination.

5. Construction of the Separation Boundary by the Combined Hodograph Without an Initial Point

Let us assume that the position of the initial point of the refracted waves is unknown. Here it becomes impossible to delineate exactly the regions of registration of the reflected and refracted waves. As a consequence of this it is impossible to interpret the parts of the hodograph in the region of the initial point, since it is unknown whether this part corresponds to the hodograph of the reflected or of the refracted waves. If this part is not interpreted, then one obtains unavoidably discontinuities in the separation boundary and the comparison of the sections of the reflecting and refracting boundaries becomes difficult.

We shall show that if the position of the initial point is unknown, it is possible to determine uniquely the position of the separation boundary by means of the entire combined hodograph.

At the initial point the following conditions are

satisfied:

Corresponding to the initial point of the hodograph of refracted waves is the point on the separation boundary, at which a section of the boundary, constructed by the hodograph of reflected waves, is tangent to the section of the boundary, constructed by the hodograph of reflected waves.

Correspondingly, the elements of the separation boundary, constructed by this portion of the hodograph coincide with each other when it is interpolated either by the formulas for the reflected waves or by the formulas for the refracted waves. If one employs, on the other hand, the formulas for the determination of the depths and angle of inclination of the separation boundary for any part of the combined hodograph, assuming this part to be the initial one, it is possible to obtain different values of these quantities when they are calculated by the formulas of reflected and refracted waves.

We shall assign different values to the coordinates of the initial points, shifting over the combined hodograph, and for each of the positions of the initial point we shall construct the separation boundary.

In the interpretation of the part of the hodograph ahead of the initial point, by means of the methods used for reflected waves, a separation boundary is obtained which we shall call arbitrarily #reflecting". The extent of this boundary depends on the position assumed for the initial point. The greater the abscissa of the initial point, the longer will be the "reflecting" boundary. This boundary will coincide with the true separation boundary when it is constructed by the section of the combined hodograph, corresponding to the hodograph of reflected waves. In the construction of the "reflecting" boundary by means of the section of the combined hodograph corresponding to the hodograph of the refracted wave, one obtains an erroneous shape of the separation boundary and an erroneous depth for it.

In the interpretation of the part of the hodograph past the assumed initial point, using the methods for the refracted waves, a family of separation boundaries is ob-

tained. The position of each of the separation boundaries is determined by the depth at the reference point. By way of such a point it is natural to take the depth at the initial point, determined in the interpretation of the part of the hodograph, which belongs to the hodograph of reflected waves. We shall arbitrarily call these boundaries "refracting".

The "refracting" boundaries intersect the "reflecting" boundary. Among all these boundaries there is only one pair of "refracting" and "reflecting" boundaries, which are tangent to each other. According to the above, this indeed determines the true position of the separation boundary.

In practice the construction of the separation boundaries is conveniently carried out by the method of time fields [52], used for the interpretation of the hodographs of reflected and refracted waves. From the constructed field of the isochrons it is possible to determine the position of the "reflecting" boundary in the entire family of "refracting" boundaries.

Let us explain this method using as a simplest example the horizontal separation boundary for constant values of the velocities in the covering medium, V_1, and in the refracting medium, V_2. On Fig. 130, in the upper part, is shown a combined hodograph, constructed for V_1 = 2 km/sec, V_2 = 4 km/sec, and H = 1 km.

Let us use the garphic method for solving this problem; in this case this method is the clearest and simplest.

We shall interpret the combined hodograph either in its entirety or the hodograph that includes the hodograph of the reflected waves and part of the hodograph of refracted waves, assuming it arbitrarily to be the hodograph of reflected waves. As a result we obtain a certain separation boundary (solid line). This boundary is straight and coincides with the true boundary in the section corresponding to the actual hodograph of reflected waves, and differs from the true in the section corresponding to the actual hodograph of the refracted waves.

We shall interpret the combined hodograph, which includes the hodograph of refracted waves and a part of the hodograph of reflected waves, assuming it to be arbitrarily the hodograph of refracted waves. We obtain a certain boundary (dotted lines). A section of this boundary, corresponding to the actual hodograph of the refracted waves, has a straight-line form, the same as a true separation boundary; the section corresponding to the actual hodograph of reflected waves, has a curved form, different from the form of the true separation boundary. The position of this boundary in depth depends on the position of the initial point of the hodograph of refracted waves. By specifying different values of the abscissas of the initial points, we obtain a family of boundaries (dotted lines), each of which intersects the boundary (solid line) at an angle different from zero. The true position of the separation boundary is determined from the condition that one of the refracting boundaries is tangent to the reflecting boundary (solid line).

In the lower part of Fig. 130 are given the results of the construction of the refracting and reflecting boundaries at different abscissas of the initial point (x_1, x_2, x_3, x_4). The heavy lines (solid and dotted) show the true position of the separation boundary, which is obtained at an abscissa x_4 for the initial point.

Thus, in the presence of a combined hodograph without a fixed initial point, it is possible to determine uniquely the position of the separation boundary.

This conclusion and the same proof hold also in the general case of a curved separation boundary and any specified law of distribution of the velocities in the covering medium.

6. Use of the Combined Method

The use of the combined method is possible in those regions, where the method of reflected waves and the correlated method of refracted waves are applicable to some extent separately.

Experience in experimental seismic operations has shown that in practically all the regions it is possible to employ these two methods to some extent or another.

Depending on the seismogeological conditions, the following cases arise:

1) All or several separation boundaries contained in the section are accessible for study by both methods; 2) some boundaries can be studied with the aid of the reflections and the others with the aid of the method of refractions, and 3) in some sections it is possible to employ the method of reflections, and in others the method of refractions. The combined method has the greatest advantages in the first case. In each of the succeeding cases the capabilities of the combined method are reduced somewhat, but invariably the combined method makes it possible to obtain more complete and more exact results than each of the other methods separately.

1) In the former case a mixed correlation is possible by phases of refracted and reflected waves. The waves corresponding to a definite separation boundary can be traced in sections closer to the point of explosion by phases of reflected waves, and at far sections (beyond the initial points of the hodograph of refracted waves) they can be traced by phases of refracted waves. This makes it possible to trace the waves corresponding to one and the same separation boundary at greater distances and with less observations, than by means of the individual methods. In mixed correlation less explosion points are necessary, which reduces the number of interrelation elements by mutual points and leads to an increase in the reliability of the correlation. In addition, it is possible to verify the correctness of the correlation of the waves of one type by means of correlation of waves of another type.

In joint interpretation of these two methods, as shown above, it is possible to obtain greater accuracy and uniqueness of the results.

2) In the second case a simultaneous study of the refracting and reflecting boundary is possible, which makes it possible to investigate the section more completely.

In some cases it is easier to investigate greater depths with the aid of the method of reflection than with the aid of the method of refraction, and the method of refraction makes it possible to investigate the smallest depths, which are unaccessible to the method of reflections.

3) In the third case, in the investigation of the data obtained by the method of refracted waves it is possible to employ information on the average velocities, obtained in the interpretation of the hodographs of the reflected waves, registered in the neighboring or closely located section.

In this case it is possible to study a greater area than by means of each of the methods separately; for example, sections which are inaccesible to investigation with the aid of the method of reflections, because of interference produced by surface waves, can be investigated with the aid of the method of refractions.

The ever increasing complexity of the problems, which must be solved by seismic methods, requires an ever increasing accuracy and detailed prospecting. As has been shown by the experience with experimental investigations and by an examination of many problems of interpretation and methodological character, this can be reached most effectively in the combined utilization of the method of reflected waves and the correlated method of refracted waves.

When using the combined method it is possible to study more completely the structure of the medium, than by using each method separately. A more complete study of the velocity section of the medium, is possible, a study of a larger number of separation boundaries, of a larger interval of depths, and greater areas than by the method of reflected waves alone or by the method of refracted waves alone. When employing the combined method it is possible to increase the accuracy of the results. A comparison of the data of the interpretation of the hodographs of reflected waves in the hodographs of refracted waves, forming the combined systems, makes it possible to refine the position of the separation bounda-

ries and at the same time to refine the information concerning the velocity section of the covering medium.

An examination of the systems of combined hodographs and a comparison of these with homogeneous systems shows that the combined systems are irreplaceable by systems of hodographs of only reflected or only refracted waves, as regards completeness and accuracy of the results obtained.

Bibliography

1. Berzon, I. S. Hodographs of Multiply-Reflected, Reflected-Refracted, and Refracted-Reflected Waves. Izv. AN SSSR, ser. geogr. i geofiz. (News of the Academy of Sciences USSR, Geographic and Geophysical Series,) Vol. VI, No. 6, 1942.
2. Berzon, I. S. Interpretation of Transverse Hodographs of Refracted Waves. Trudy ITG AN SSSR (Works of the ITG, Academy of Sciences USSR), Vol. II, No. 2, 1946.
3. Berzon, I. S. Three Dimensional Problem of Interpretation of Hodographs of Refracted Waves. Trudy ITG, AN SSSR, Vol. II, No. 2, 1947.
4. Berzon, I. S. On the Determination of the Trajectories of Seismic Rays and Time Fields in Media with Variable Velocities. Izv. AN SSSR, ser. geogr. i geofiz., Vol. XIII, No. 6, 1948.
5. On the Determination of Seismic Velocities from the Initial Points of Surface Hodographs of Mintrop Waves. Izv. AN SSSR, ser. geogr. i geofiz. Vol. XIII, No. 6, 1948.
6. Berzon, I.S. Method of Solution of Three Dimensional Problem of Interpretation of Hodographs of Mintrop Waves in the Case of Refracting Boundaries of Arbitrary Forms. Izv. AN SSSR, ser. geogr. i geofiz, Vol. XIII, No. 6, 1949.
7. Berzon, I. S. On Certain Problems in the Kinematics of Propagation of Diffracted Seismic Waves. Trudy GEOFI AN SSSR (Works of the Geophysics Institute Academy of Sciences USSR), 9(136), 1950.
8. Berzon, I. S. On the Determination of the Function of Divergence for Refracted Waves from Experimental Data. Izv. AN SSR, ser. geogr. i geofiz, Vol. XV, No. 4, 1951.
9. Berzon, I. S. On the Disclosure of the Dynamic Features of Seismic Recordings under Different Ratios of Sensitivities of the Channels. Izv. AN SSSR, ser. geogr. i. geofiz, Vol. XV, No. 6, 1951.
10. Berzon, I. S., Yepinat'yeva, A. M. On Seismic Screening. Izv. AN SSSR, ser. geogr. i geofiz, Vol. XIV, No. 6, 1950.
11. Berzon, I. S. On Seismic Waves Propagating in a Vertically-Stratified Medium. Izv. AN SSSR, ser. geofiz, No. 3, 1952.
12. Vavilov, S. I. Microstructure of Light (Investigations and Outlines). Moscow, Publishing House of the Academy of Sciences USSR, 1950

13. Veytsman, P. S. On the Fullment of the Principles of Reciprocity in Seismics. Izv. AN SSSR, ser. geogr. i geofiz, Vol. XII, No. 3, 1948.
14. Gamburtsev, G. A. Seysmicheskiye metody razvertki (Seismic Methods of Prospecting), Part 1, Moscow-Leningrad, 1937; Part 2, Moscow- Leningrad, 1938 OMTI.
15. Gamburtsev, G. A. On the Possibility of Separating Transverse Reflected Waves in Seismic Prospecting by the Method of Reflections. Izv. AN SSSR, ser. geogr. i geofiz, Vol. III, No. 2, 1939.
16. Gamburtsev, G. A. O the Correlation Method of Registration of Refracted Waves. Izv. AN SSSR, ser. geogr. i geofiz, Vol. VI, No. 2, 1942.
17. Gamburtsev, G. A. In Incomplete Systems of Hodographs of Refracted Waves. Izv. AN SSSR, ser. geogr. i geofiz, Vol. VIII, No. 2--3, 1944.
18. Gamburtsev, G. A. On One Form of Area Measurement in Prospecting by the Correlated Method of Refracted Waves. DAN SSSR (Transactions, Academy of Sciences USSR), Vol. XLIII, No. 6, 1944.
19. Gamburtsev, G. A. On Waves Caused by a Moving Source in a Solid Elastic Medium. Izv. AN SSSR, ser. geogr. i geofiz, Vol. X, No. 1, 1946.
20. Gamburtsev, G. A. On the Mapping of Seismic Fields. Izv. AN SSSR, ser. geogr. i geofiz, Vol. X, No. 1, 1946.
21. Gamburtsev, G. A. Correlated Methods of Observation in Prospecting by the Method of Refracted and Reflected Waves. Izv. AN SSSR, ser. geogr. i geofiz, Vol. X, No. 1, 1946.
22. Gamburtsev, G. A. Development of the Experimental Seismology in the Soviet Union. Izv. AN SSSR, ser. geogr. i. geofiz, Vol. XI, No. 5, 1947.
23. Gamburtsev, G. A., Deryagin, B. B., et al. Prikladnaya geofizika (Applied Geophysics), No. 2, ONTO-GTDI, 1934.
24. Gamburtsev, G. A., Riznichenko, Yu. V. On Phase Correlation DAN SSSR, Vol. L, 1945.
25. Gamburtsev, G. A., Riznichenko, Yu. V., Berzon, I. S. On the Prospecting Capabilities of the Correlated Method of Refracted Waves. DAN SSSR, Vol. LI, No. 7, 1946.
26. Gamburtsev, G. A., Riznichenko, Yu. V., Berzon, I. S., Yepinat'yeva, A. M. The Combined Method of Seismic Prospecting. DAN SSSR, Vol. LI, No. 6, 1946.
27. Gamburtsev, G. A., Riznichenko, Yu. V., Polshkov, M. K., Karus, Ye. V., Yepinat'yeva, A.M., and Kosminskaya, I. P. The Correlated Method of Refracted Waves in the Eastern Apsheron. DAN SSSR, Vol. L, 1945.
28. Dakhnov, V. N., Ryabinkin, A. A., and Shneyerson, B.L. Geofizicheskiye metody razvedki neftyanykh mestorozhdeniy (Geophysical Methods of Prospecting for Oil De-

posits), Gostoptekhizdat, Moscow-Leningrad, 1939.
29. Dreyer, I. L. Urozhay. "Radio" 1, 1947.
30. Yedynyye normy vyrabotki na polevyye geofizicheskiye raboty (Unified Norms of Work in Field Geophysical Operations). Gostoptekhizdat, 1949.
31. Yepinat'yeva, A. M. On Hodographs of Reflected Waves in the Presence of a Vertical Velocity Gradient. Izv. AN SSSR, ser. geogr. i geofiz, Vol. X, No. 1, 1946.
32. Yepinat'yeva, A. M. Combination of Seismic Methods of Prospecting (Candidate's dissertation), Moscow, 1946.
33. Yepinat'yeva, A. M. On the Accuracy of the Determination of Boundary and Layer Velocities by Seismic Data. Trudy GEOFI AN SSSR, Vol. 1, 1948.
34. Yepinat'yeva, A. M. On the Average Velocity of Propagation of Elastic Waves Under the Condition of Eastern Apsheron. Izv. AN SSSR, ser. geogr. i geofiz, Vol. XII, No. 1, 1948.
35. Yepinat'yeva, A. M. On Certain Types of Diffracted Waves, Registered in Seismic Observations. Izv. AN SSSR, ser. geogr. i geofiz, Vol. XIV, No. 1, 1950.
36. Yepinat'yeva, A. M. On the Accuracy of Determination of the Average Velocity from Initial Points of Hodographs of Refracted Waves. Razvedka nedr (Prospecting of Depths), No. 2, 1951.
37. Yepinat'yeva, A. M. Repeated Shocks in Seismic Observations. Izv. AN SSSR, ser. geogr. i geofiz, Vol. XV, No. 4, 1951.
38. Yermeyev, A. N. The Seismic Station VIRG-24, Razvedka nedr, No. 13, 1947.
39. Zaytsev, L. P., and Zvolinskiy, N. V. Investigation of a Frontal Wave, Produced at a Separation Boundary Between Two Elastic Liquids. Izv. AN SSSR, ser. geogr. i geofiz, Vol. XV, No. 1, 1951.
40. Kirnos, D. P., Koridalin, Ye. A., Massarskiy, S. I., and Rayko, M. V. Work of the Seismic Institute of the Academy of Sciences USSR on Seismic Prospecting. Trudy Seysmologich. in-ta, (Works of the Seismological Institute), No. 47, 1934.
41. Koridalin, Ye. A., and Massarskiy, S. I. Experience in Deep Seismic Prospecting. Trudy Seysmologich. in-ta, No. 106, 1941.
42. Kosminskaya, I. P. On Initial Points of Hodographs of Mintrop Waves. Izv. AN SSSR, ser. geogr. i. geofiz, Vol. X, No. 1, 1946.
43. Kosminskaya, I. P. Use of the Method of Time Fields in the Case of Variable Velocity. Izv. AN SSSR, ser. geogr. i. geofiz, Vol. X, No. 5, 1946.
44. Nastavleniye po proizvodstvy seysmorazvedochnykh rabot (Manual of Seismic Prospecting Operations), Gostoptekhizdat, 1951.

45. Pasechnik, I. P. Vibration Platform for the Investigation of Prospecting Seismographs. Izv. AN SSSR, ser. geogr. i geofiz, Vol. XIV, No. 6, 1950.
46. Petrashen', G. I. Dynamic Problems of Theory of Elasticity. Uch. Zapiski LGU, ser. matemat. (Scientific Notes of the Leningrad State University, Mathematics Series), No. 24, No. 9, 1951.
47. Puzyrev, N. I. Construction of Ray Diagrams for an Arbitrary Law of Variation of Velocity with Depth. Prikladnaya geofizika (Applied Geophysics), No. 2, 1945.
48. Rayleigh. Theory of Sound (Russian Translation), Moscow-Leningrad, 1944.
49. Riznichenko, Yu. V. On the Theory of the Seismic Hodograph. Izv. AN SSSR, ser. geogr. i geofiz, Vol. III, No. 3, 1939.
50. Riznichenko, Yu. V. Instrument for Seismic Interpretation by the Method of Time Fields. Izv. AN SSSR, ser. geogr. i geofiz., Vol., IV, 1940.
51. Riznichenko, Yu. V. On Mutual Points in the Seismic Method of Reflections. Izv. AN SSSR, ser. geogr. i geofiz., Vol. VIII, No. 213, 1944.
52. Riznichenko, Yu. V. Use of the Method of Time Fields in Practice. Prikladnaya geofizika, No. 1, 1945.
53. Riznichenko, Yu. V. Geometric Seismics of Stratified Media. Trudy ITG AN SSSR, Vol. II, No. 1, 1946.
54. Riznichenko, Yu. V. Seismic Velocities in Stratified Media. Izv. AN SSSR, ser. geogr. i geofiz, Vol. XI, No. 2, 1947.
55. Riznichenko, Yu. V. Template of Theoretical Hodographs of Reflected Waves. Izv. AN SSSR, ser. geogr. i geofiz., Vol. X, No. 5, 1946, Gosgeolizdat, Moscow, 1949.
56. Riznichenko, Yu. V. On Seismic Quasi-Anisotropy. Izv. AN SSSR, ser. geogr. i geofiz, Vol. XIII, No. 6, 1949.
57. Riznichenko, Yu. V., Ivakin, B. N., and Bugrov, V. R. Simulation of Seismic Waves. Izv. AN SSSR, ser. geogr. i geofiz., No. 5, 1951.
58. Sorokin, L. V., Ryabinkin, L. A., Uryson, V. O., and Dolitskiy, V. A. Kurs geofizicheskikh metodov rasvedki neftyanykh pestorozhdeniy (Course of Geophysical Methods of Prospecting for Oil Deposits). Gostekhizdat, Moscow-Leningrad, 1950.
59. Spravochnik ukrupnennykh smetnykh norm na geologorazvedochnyye rabody (Handbook of Increased Estimated Norms for Geological Prospecting Operations), No. II, Gosgeolizdat, 1950.
60. Shvedchikov, L. K. Twenty-Channel Seismic Station SS-12-46. Razvedka nedr, No. 2, 1947.

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